Measuring BAO correlations at z = 2.3 with SDSS DR12 Lyman-α forests

Julian Bautista - University of Utah

LINEA webinar - August 24th 2017

OUTLINE

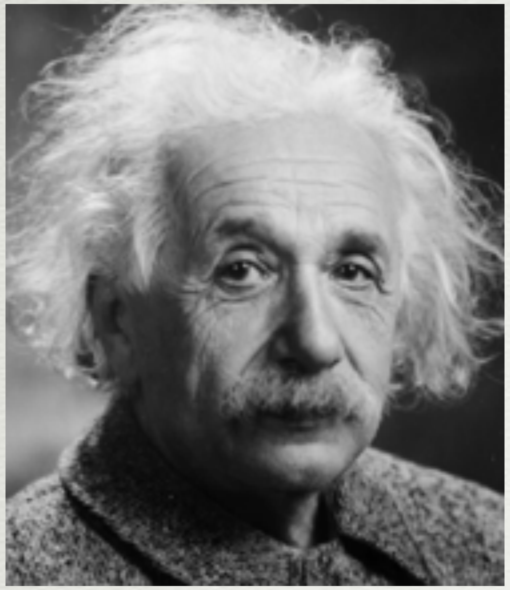
Part I

- Expansion of the Universe
- Baryon Acoustic Oscillations
- The BOSS survey

Part II

- Measuring the flux correlation function
- Results on data
- Cosmological implications
- Future

Brief history of dark energy

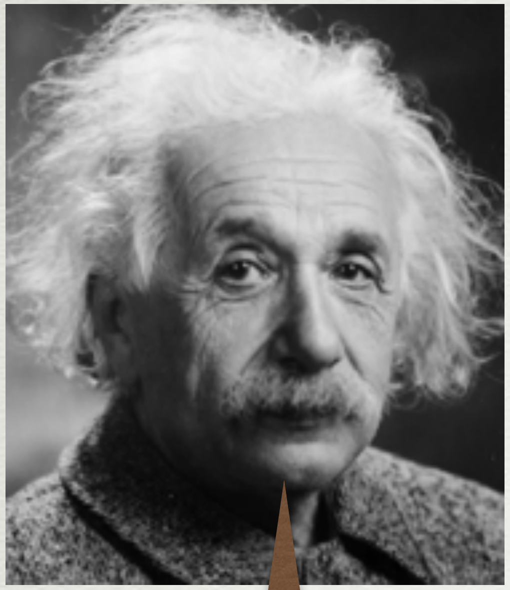


General Relativity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time ↔ $G_{\mu\nu}$

Contents ↔ $T_{\mu\nu}$



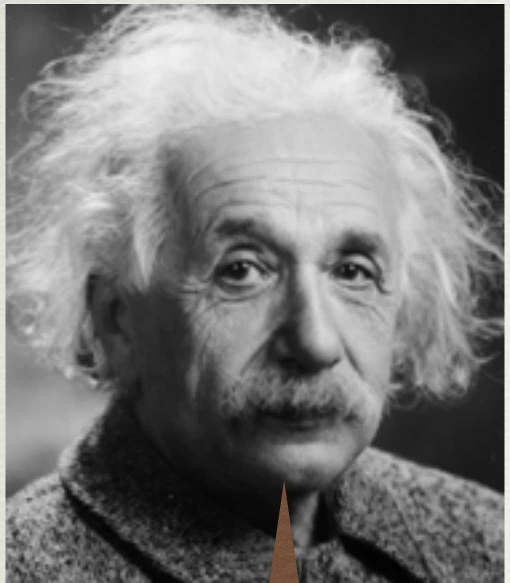
The Universe is static!

General Relativity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time

Contents



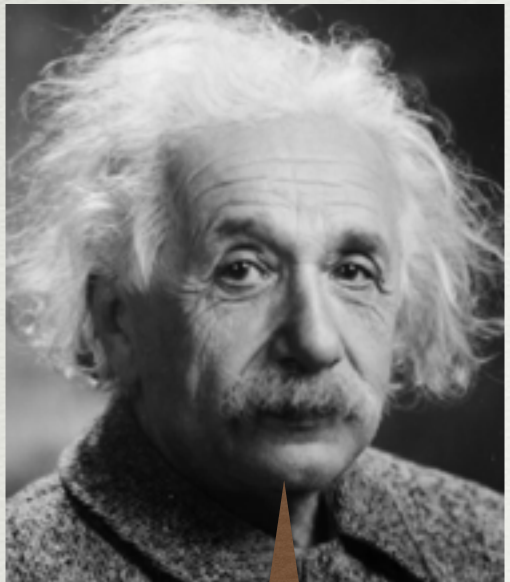
The Universe is static!

General Relativity

$$\Lambda g_{\mu\nu} + G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time ↔ $G_{\mu\nu}$; Contents ↔ $T_{\mu\nu}$

Λ
= cosmological constant
= anti-gravity
= vacuum energy



The Universe is static!

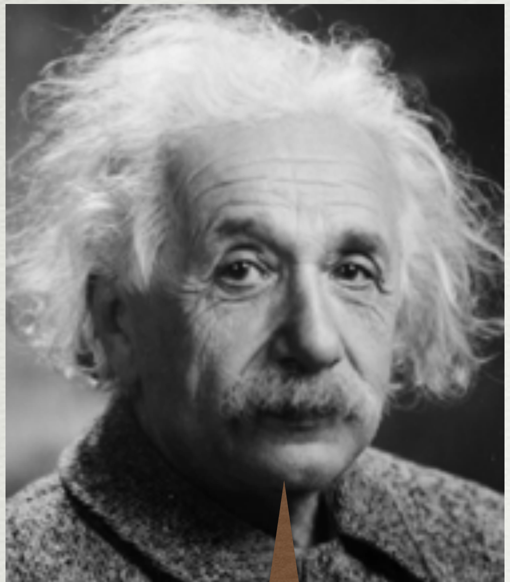
General Relativity

$$\Lambda g_{\mu\nu} + \quad G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time　　　Contents

Λ
= cosmological constant
= anti-gravity
= vacuum energy

Edwin Hubble



The Universe is static!

General Relativity

$$\Lambda g_{\mu\nu} + G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time

Contents

Λ = cosmological constant
= anti-gravity
= vacuum energy

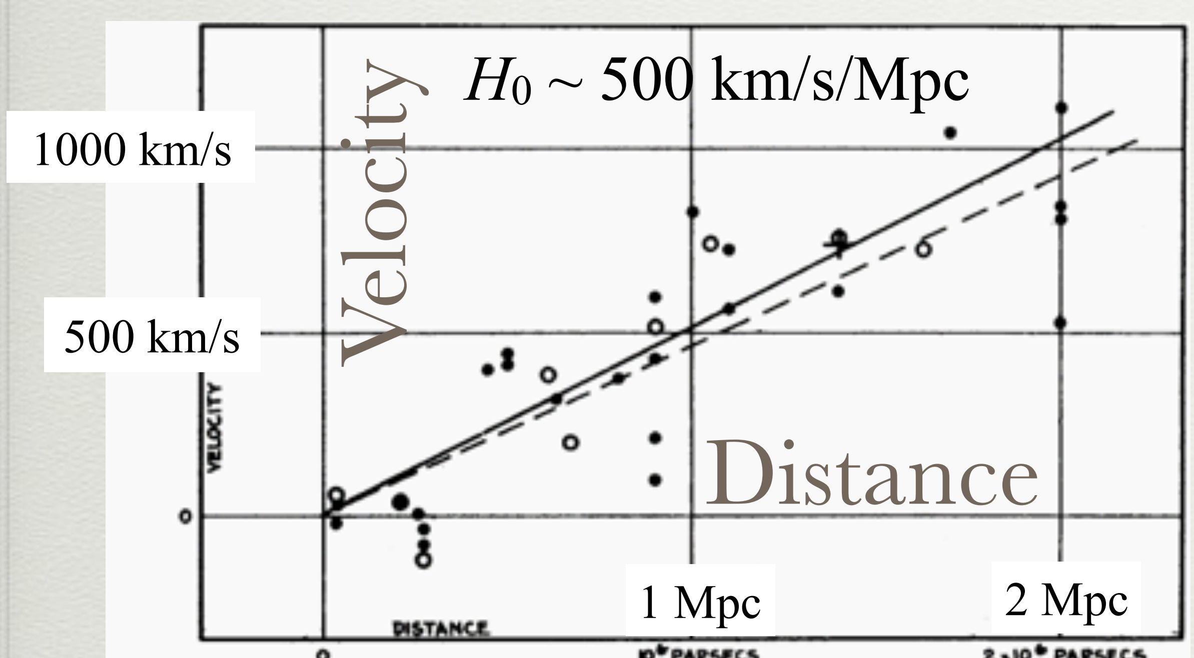
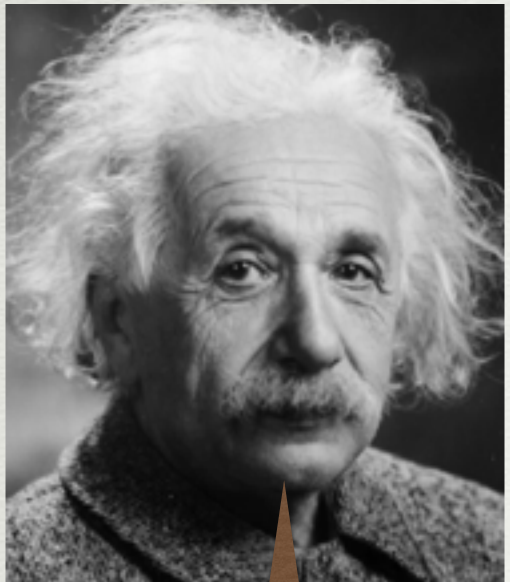


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.
(Hubble 1929)

The Universe is expanding!

Edwin Hubble



The Universe is static!

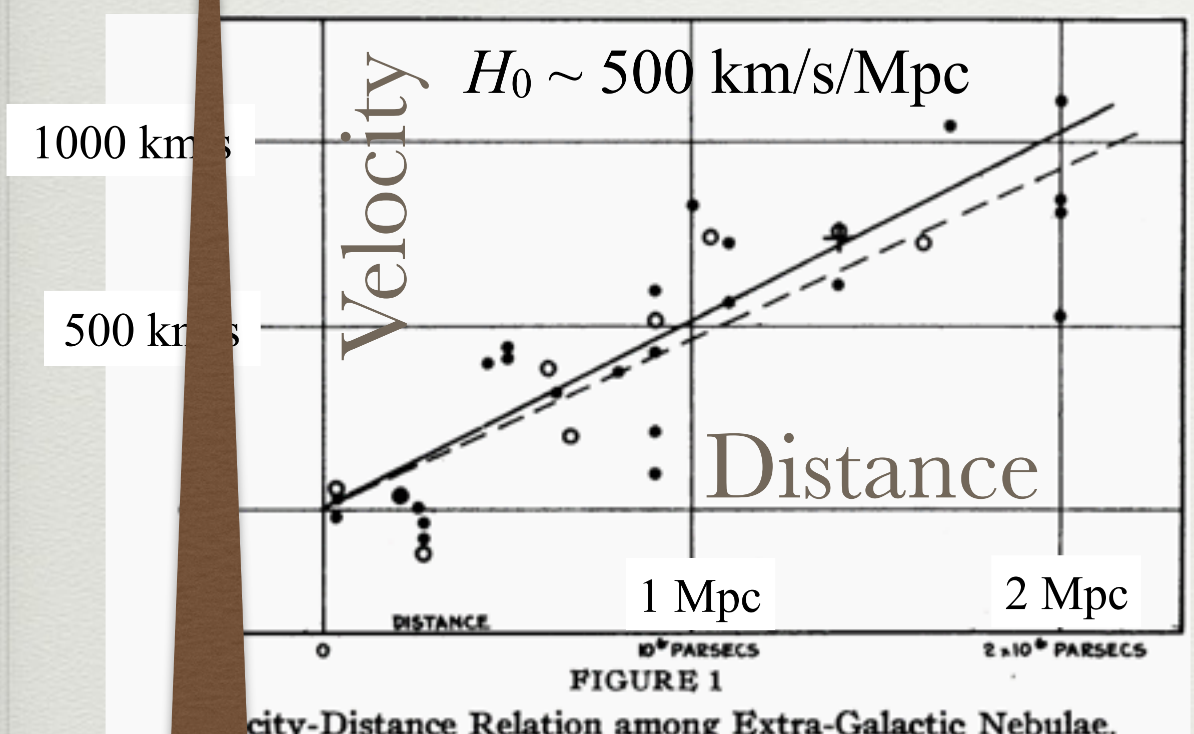
General Relativity

$$\Lambda g_{\mu\nu} + G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time

Contents

Λ = cosmological constant
= anti-gravity
= vacuum energy



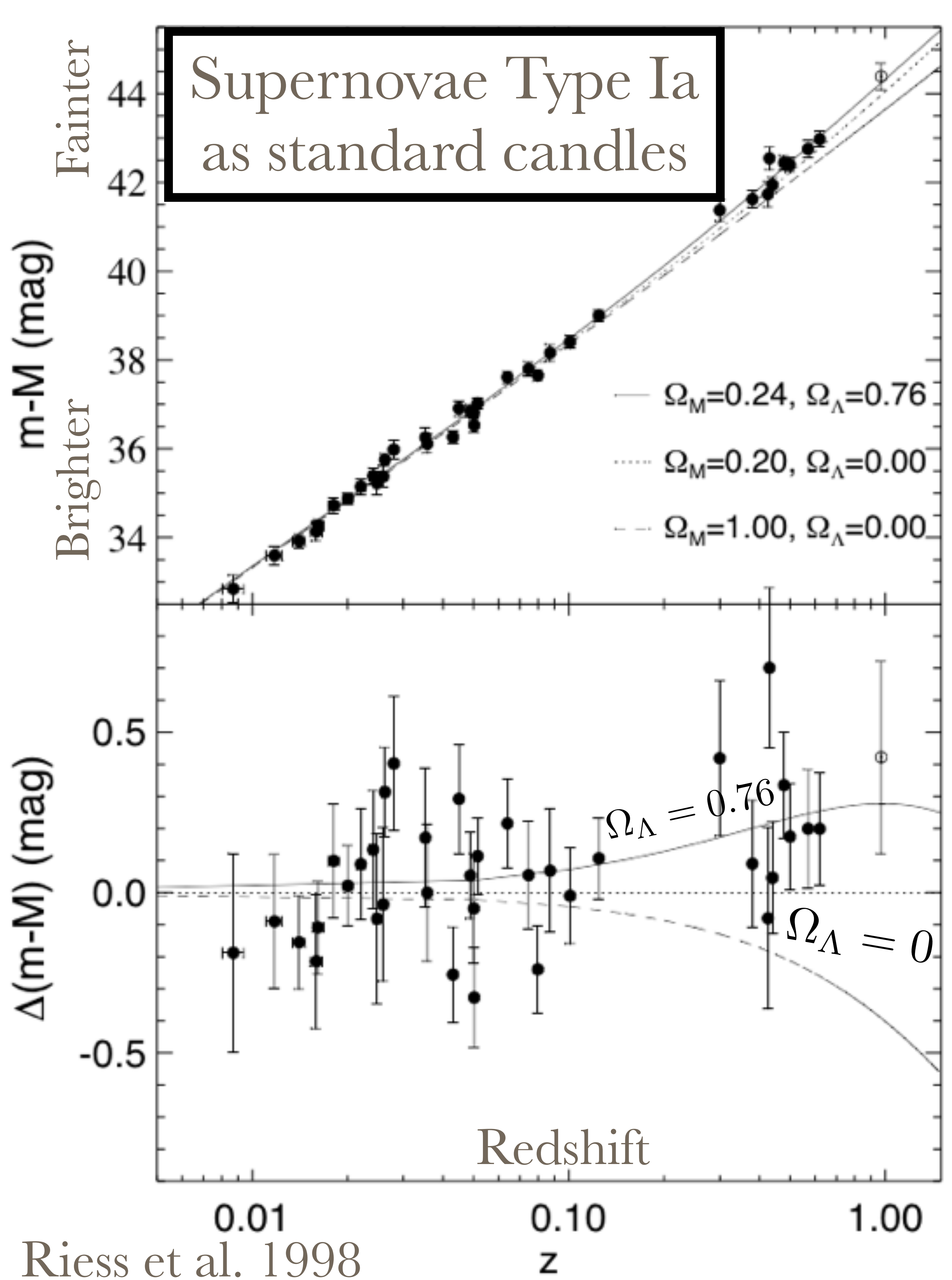
(Hubble 1929)

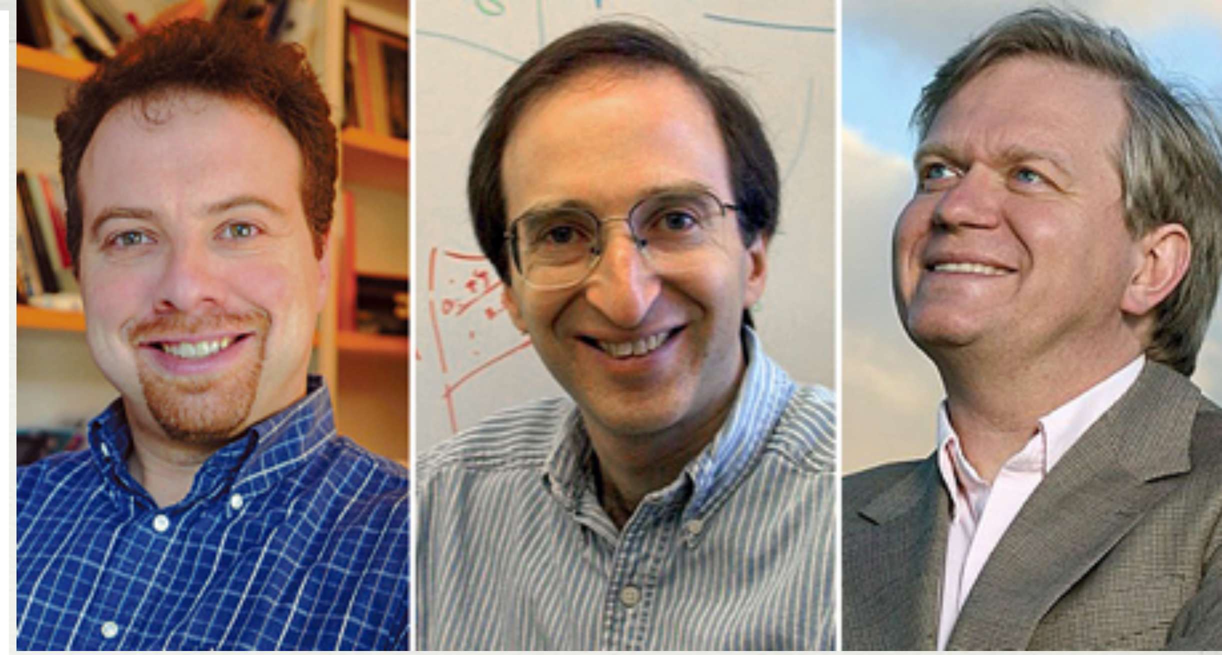
The Universe is expanding!

Edwin Hubble

The cosmological constant is the biggest mistake of my life!

70 years later…

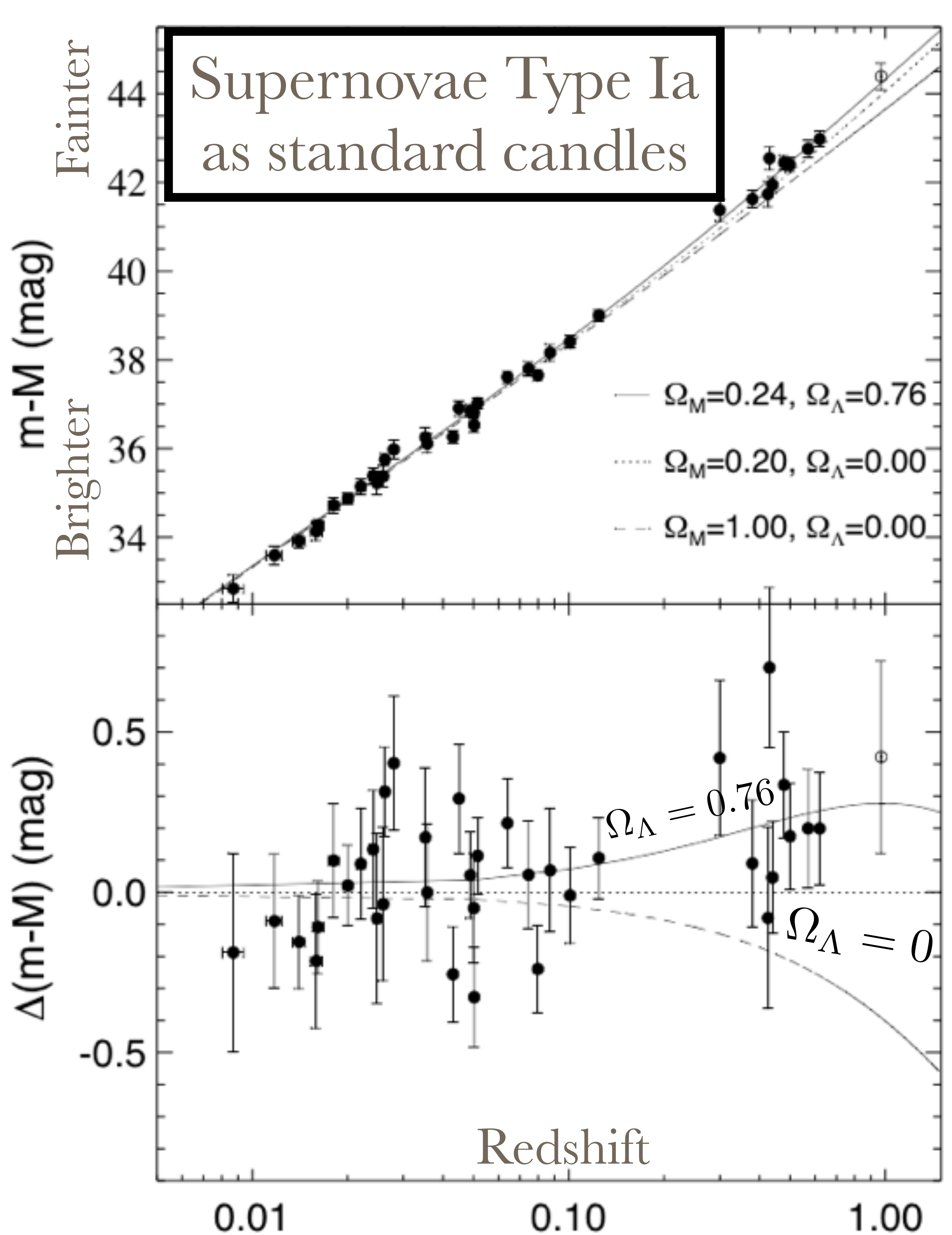




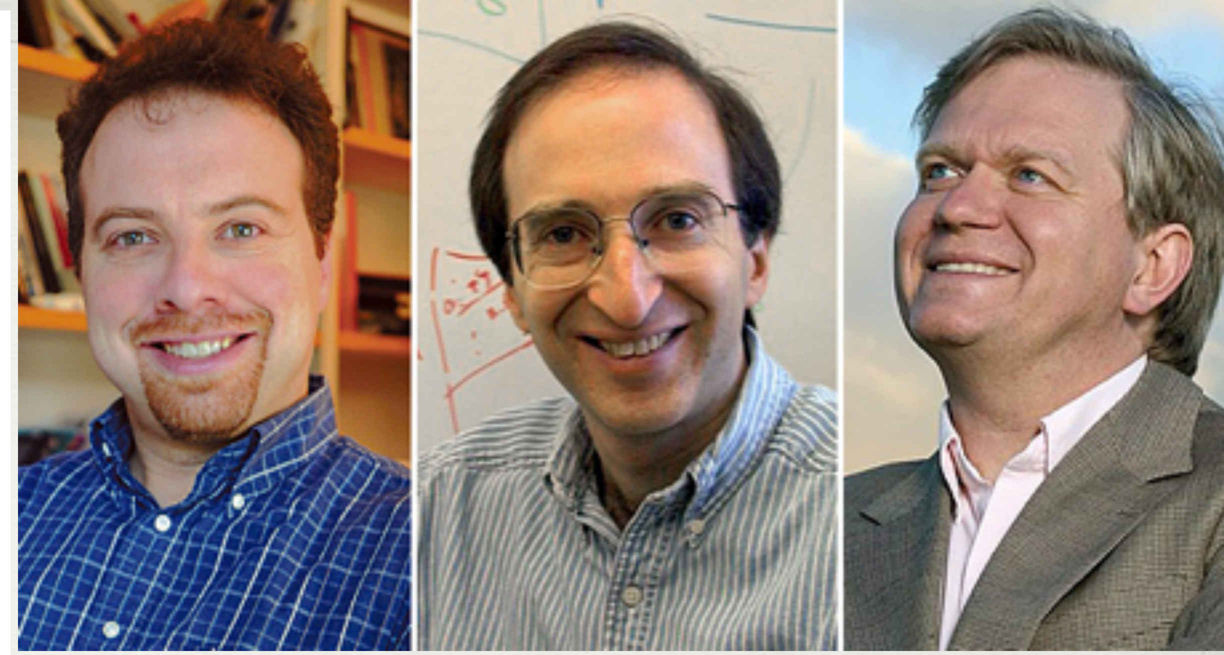
Riess

Perlmutter

Schmidt

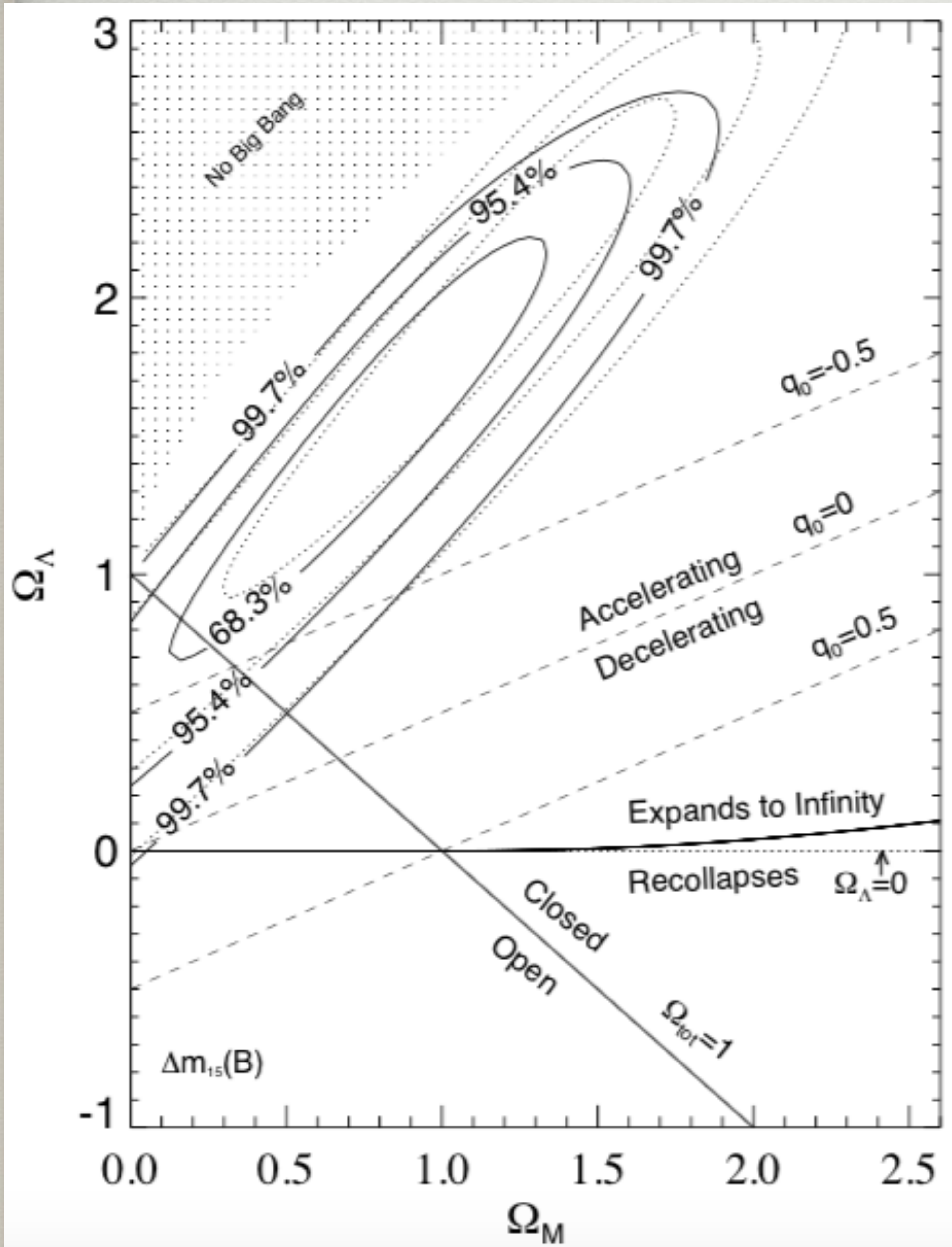


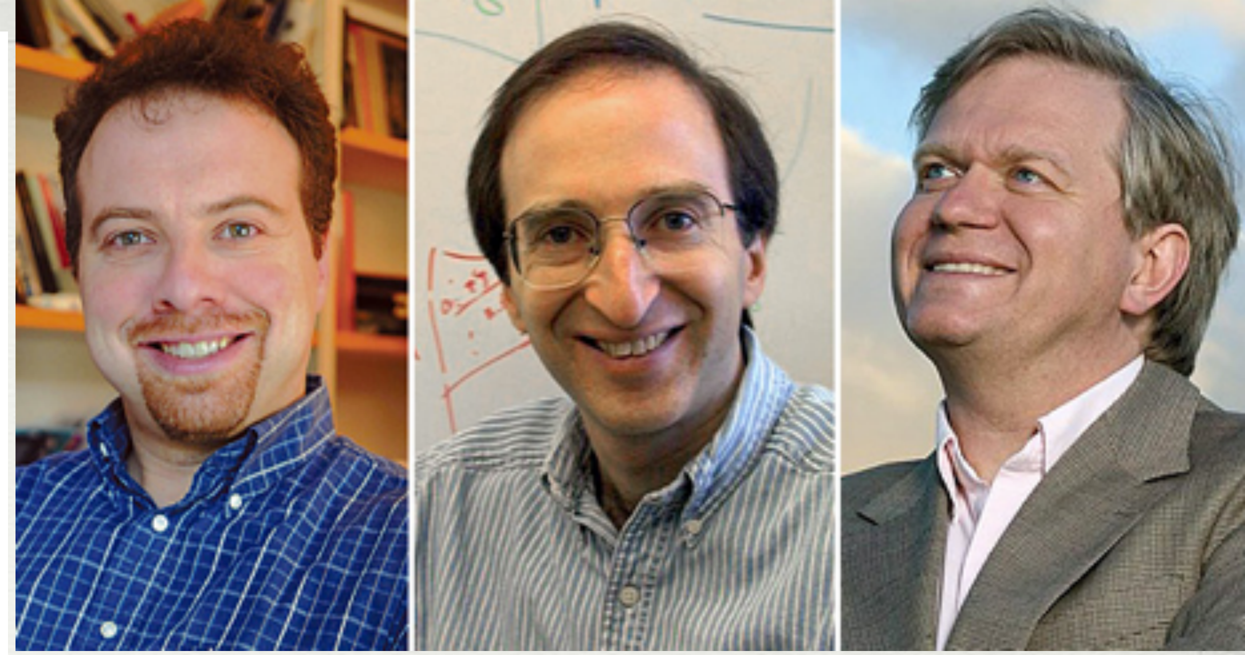
Riess et al. 1998



Riess Perlmutter Schmidt

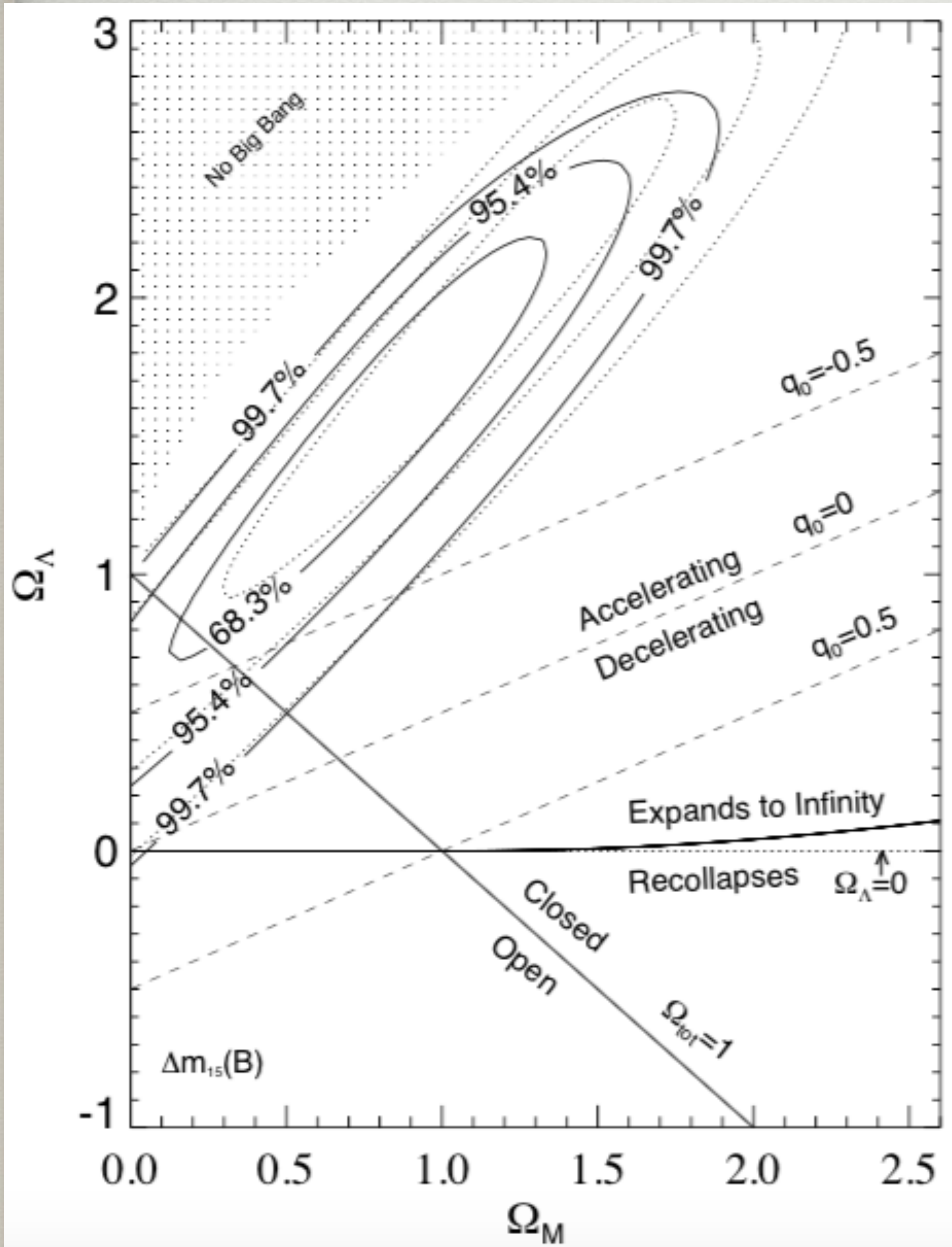
Accelerated expansion!
We need the cosmological constant!

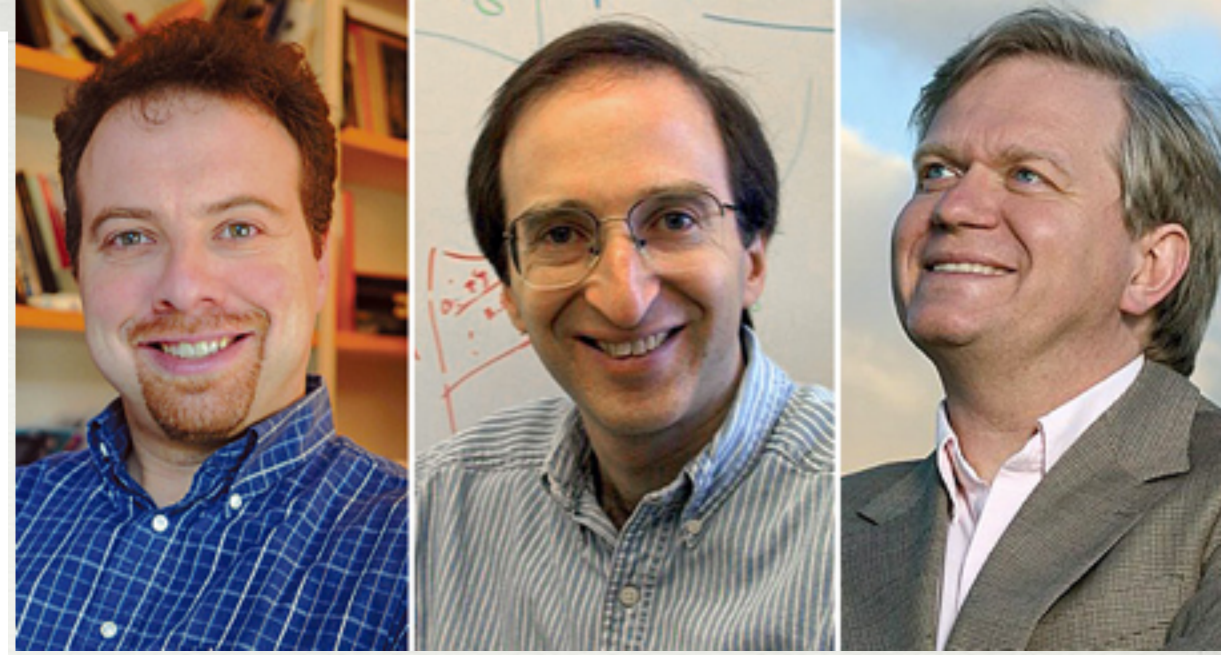




Riess Perlmutter Schmidt

Accelerated expansion!
We need the cosmological constant!

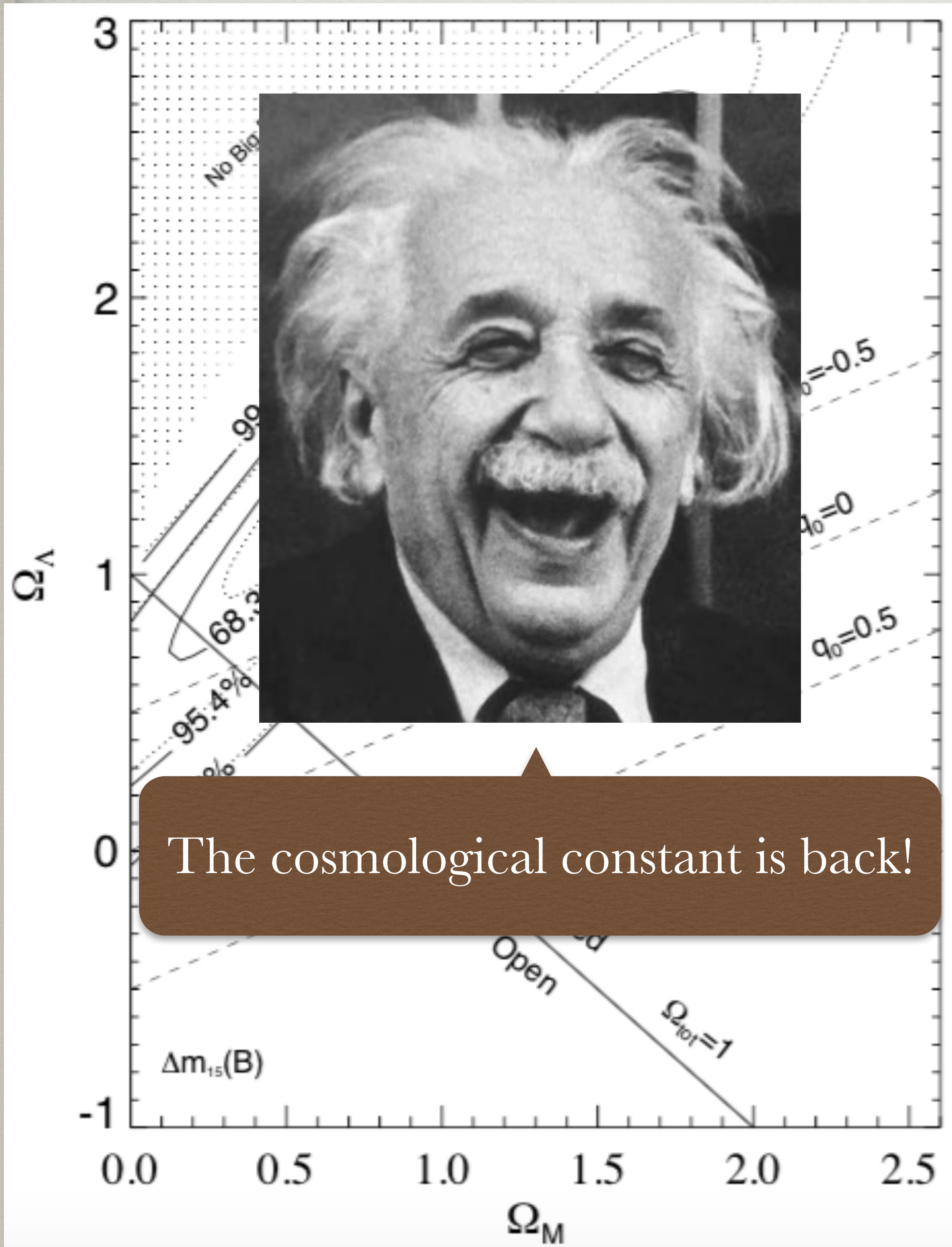




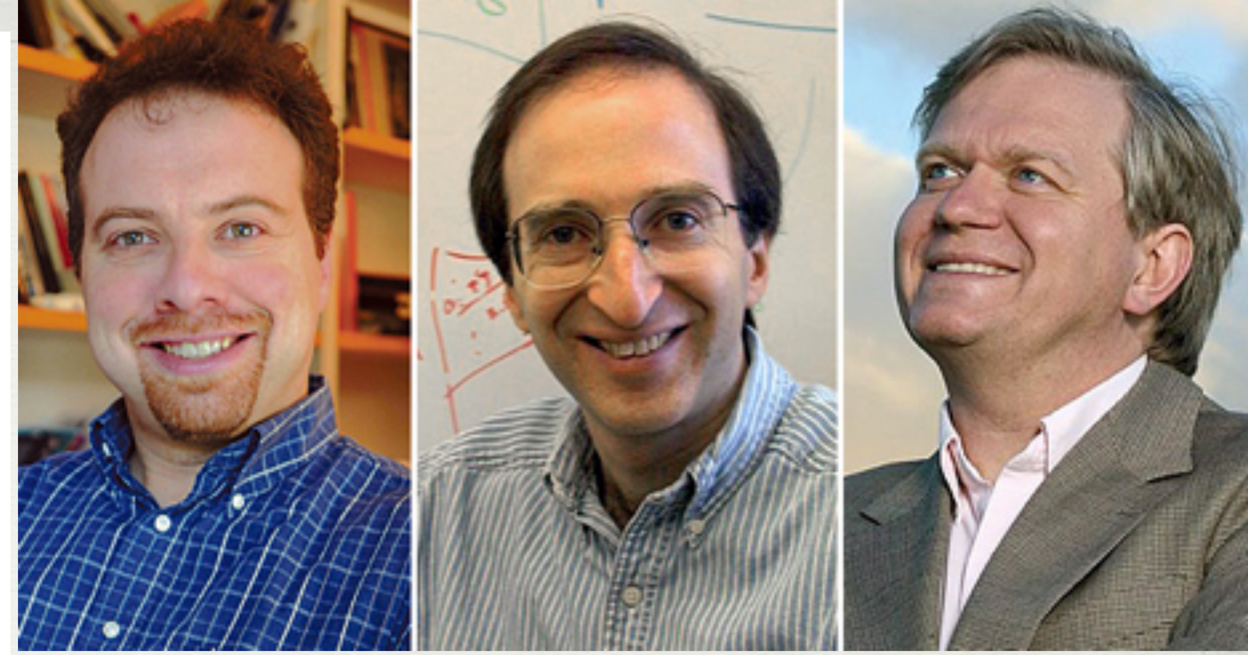
Riess Perlmutter Schmidt

Accelerated expansion!
We need the cosmological constant!

2011



The cosmological constant is back!



Riess Perlmutter Schmidt

Accelerated expansion!
We need the cosmological constant!

2011

… and the quest for dark energy begins!

Observing the expansion

Observing the expansion

- Expansion rate: $H(t) \equiv \frac{\dot{a}(t)}{a(t)}$ $t \to z$ (redshift)

Observing the expansion

- Expansion rate: $H(t) \equiv \frac{\dot{a}(t)}{a(t)}$ $\qquad$ $t \to z$ (redshift)

$$H^2(z) = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2 + \Omega_r (1+z)^4\right]$$

- H_0 → Today
- Ω_m → Dark + baryonic matter density
- Ω_Λ → **Dark energy**
- Ω_k → Curvature
- Ω_r → Radiation

Observing the expansion

- Expansion rate: $H(t) \equiv \frac{\dot{a}(t)}{a(t)}$ $\quad t \to z$ (redshift)

$$H^2(z) = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2 + \Omega_r (1+z)^4\right]$$

Today

Dark + baryonic matter density

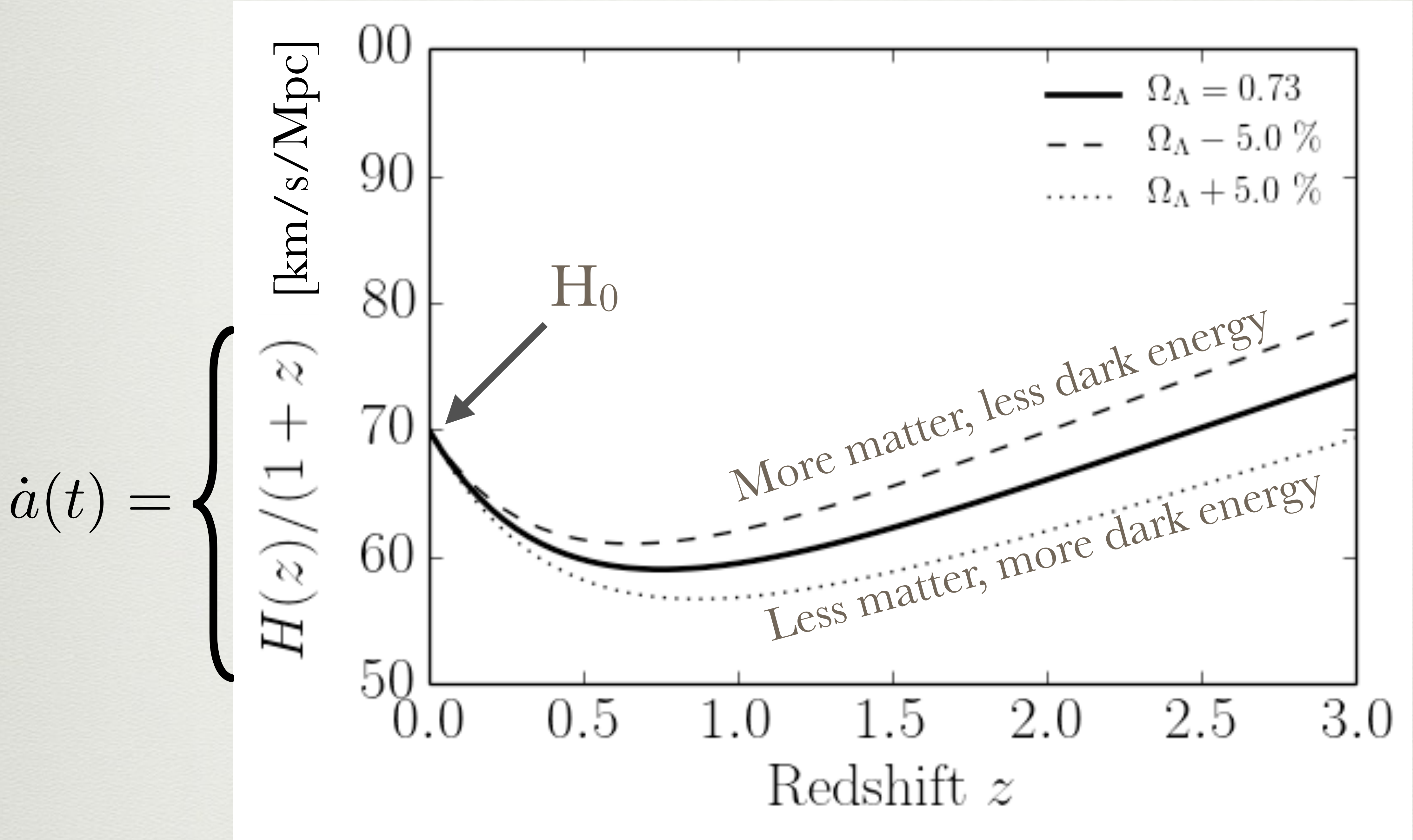
Dark energy

Curvature

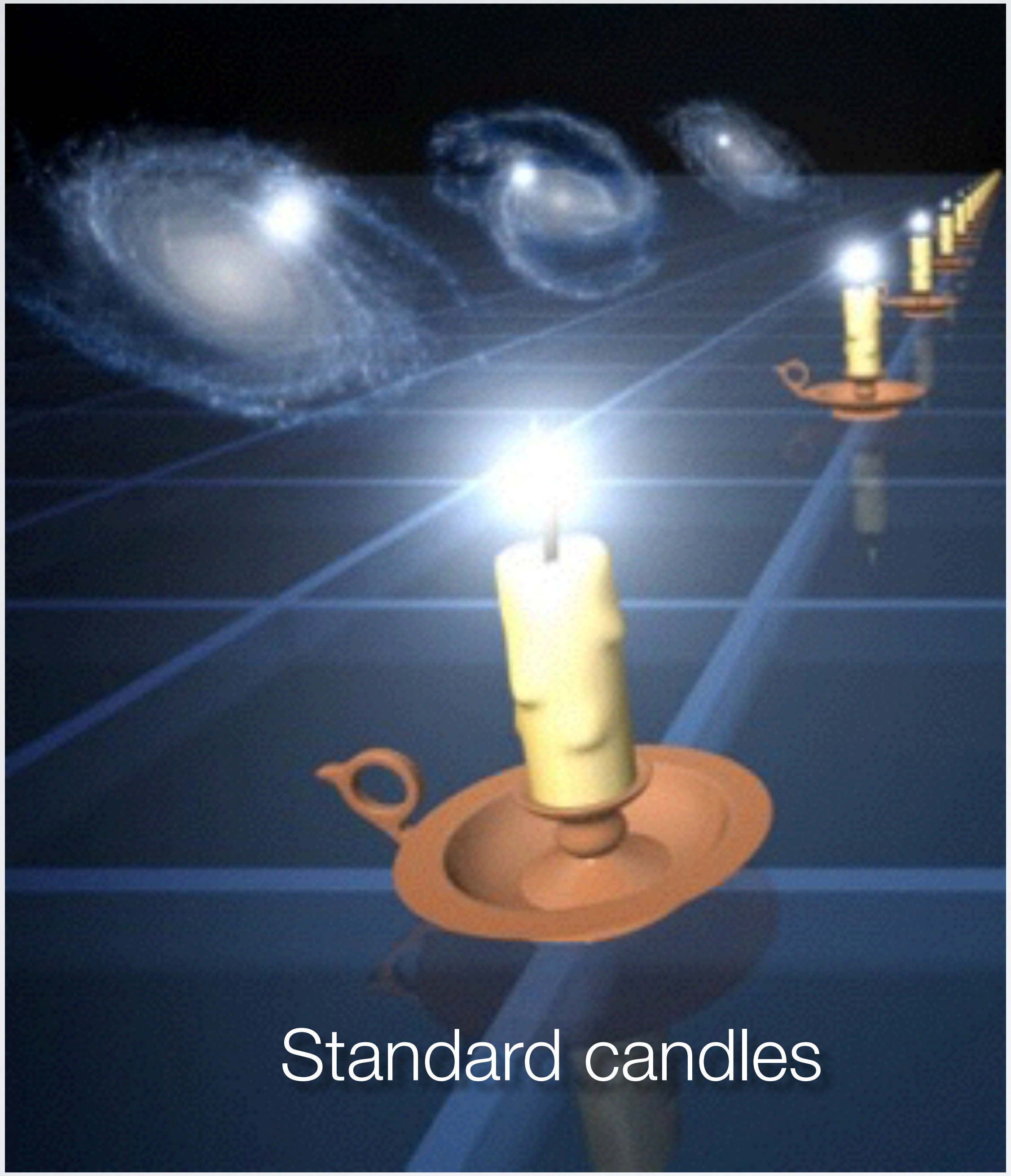
Radiation

- Distances: $D(z) \propto c \int_0^z \frac{\mathrm{d}z}{H(z)}$

$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_\Lambda\right]$$

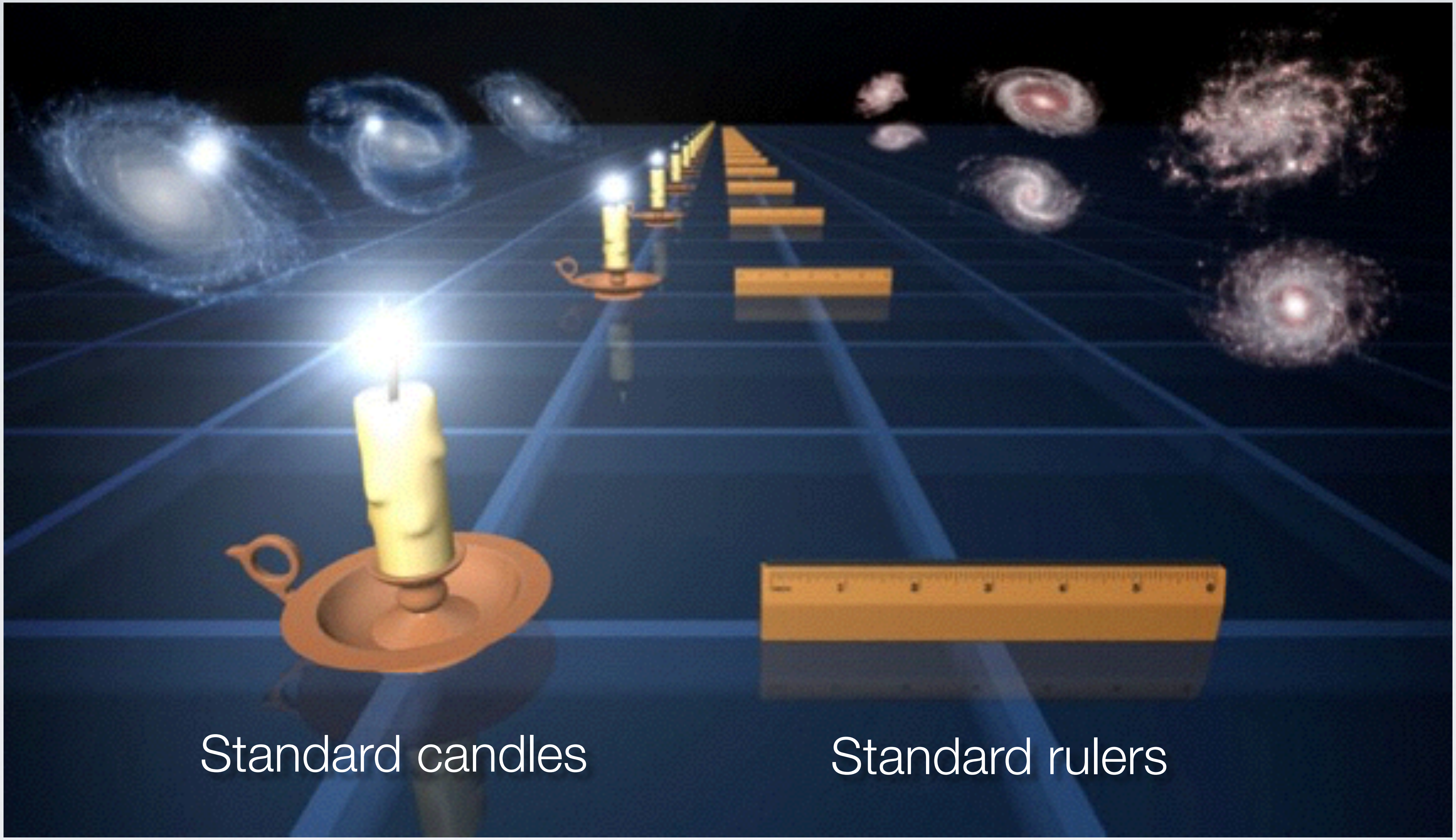


Measuring the H(z) or D(z) at many redshifts
gives us constraints on the components of the Universe



http://www.ipac.caltech.edu/

Uses ratios of D(z) assuming “constant” luminosity

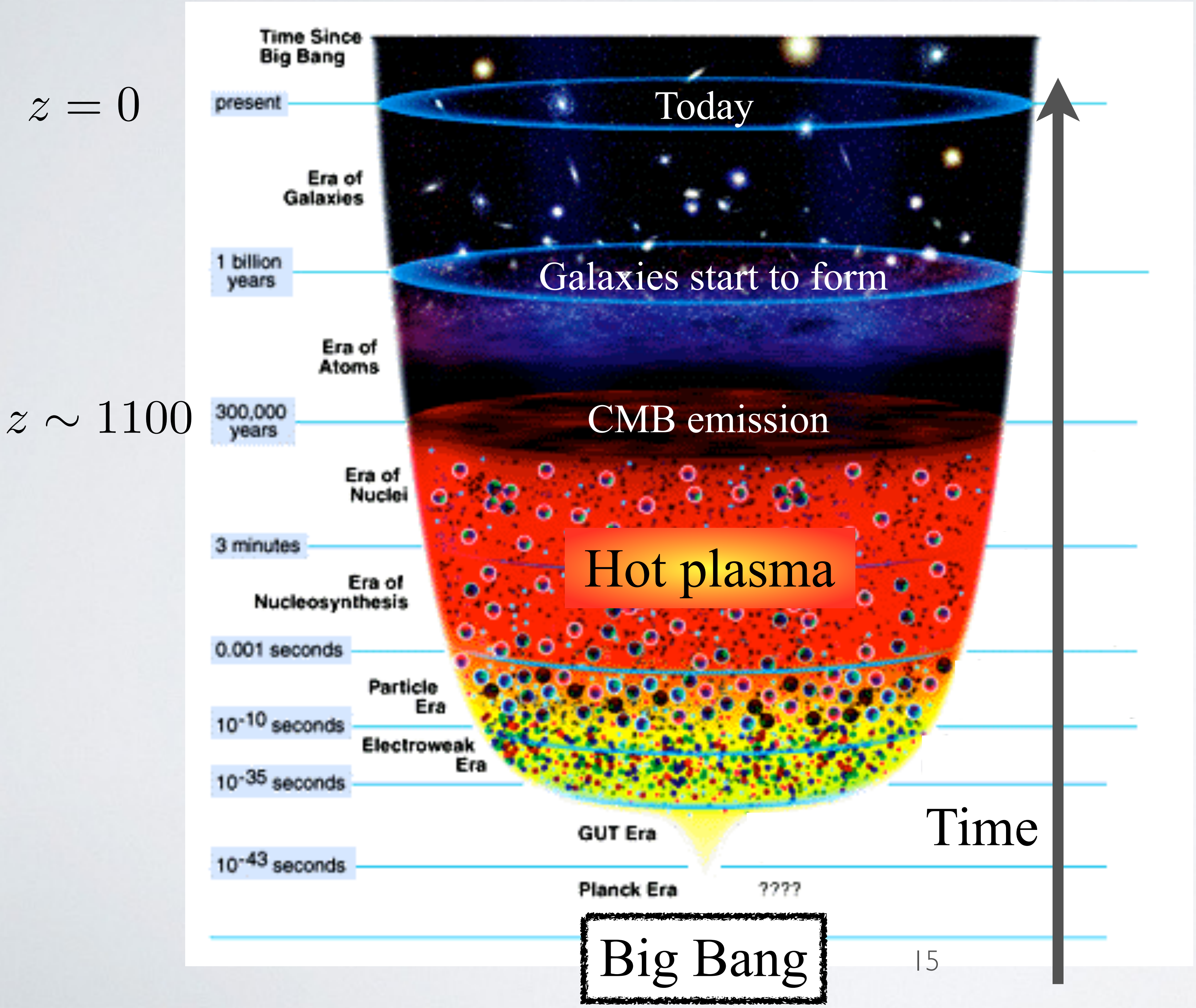


http://www.ipac.caltech.edu/

What is this standard ruler?

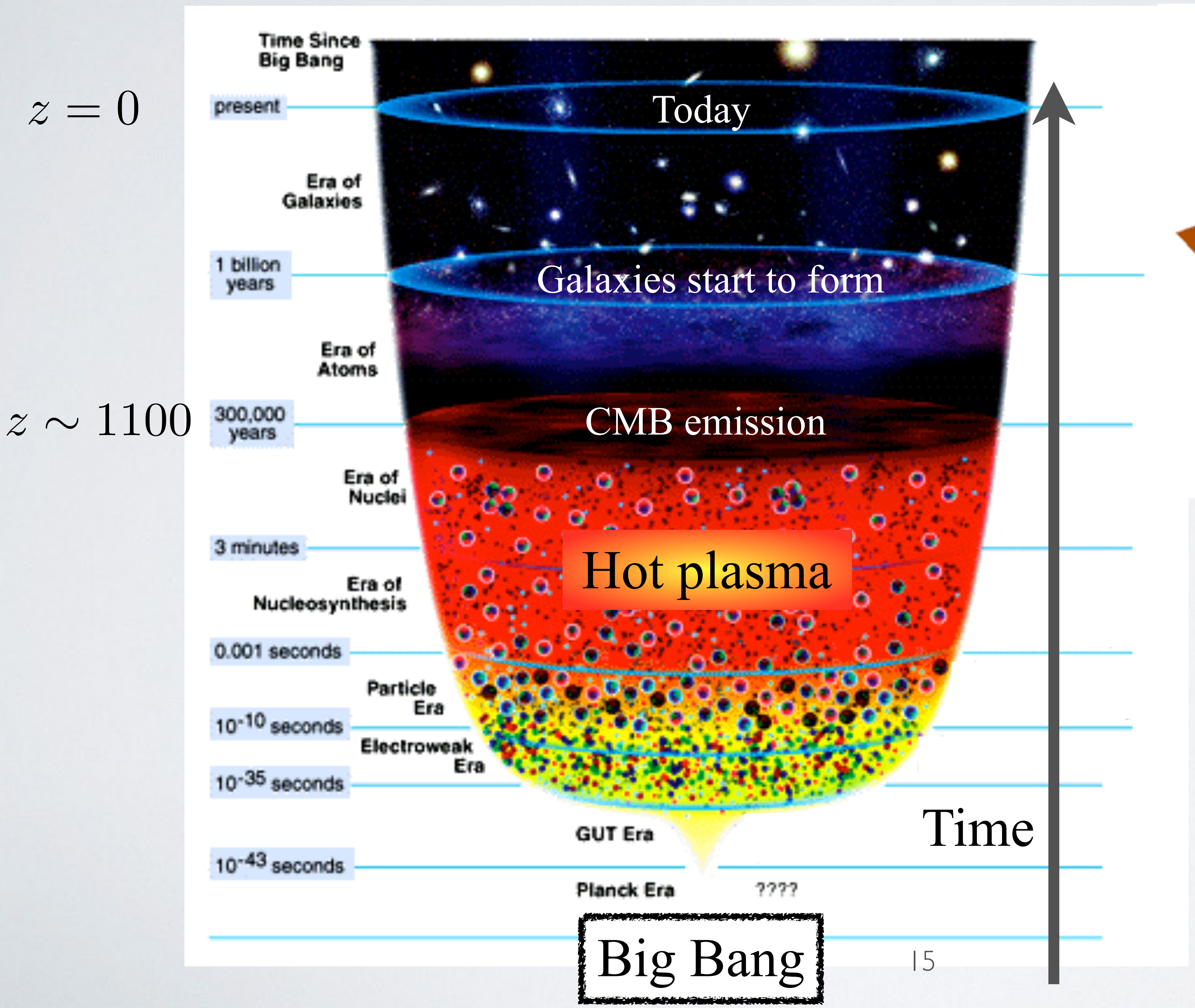
BAO

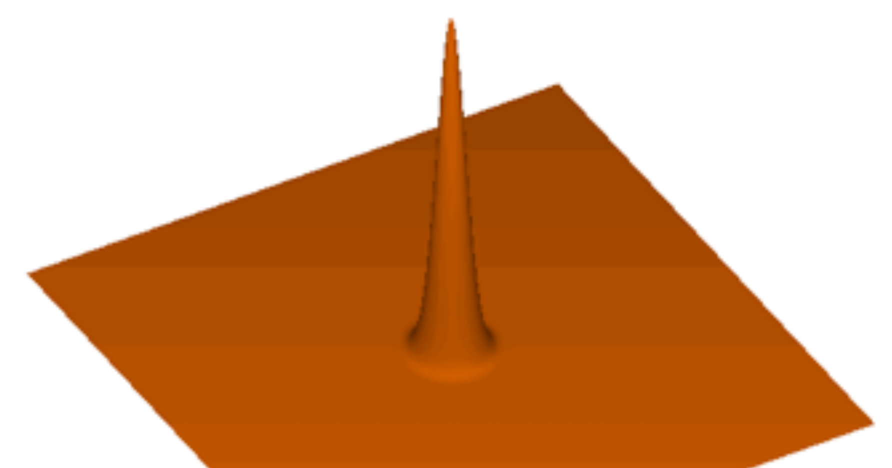
The origin of the standard ruler



BAO

The origin of the standard ruler





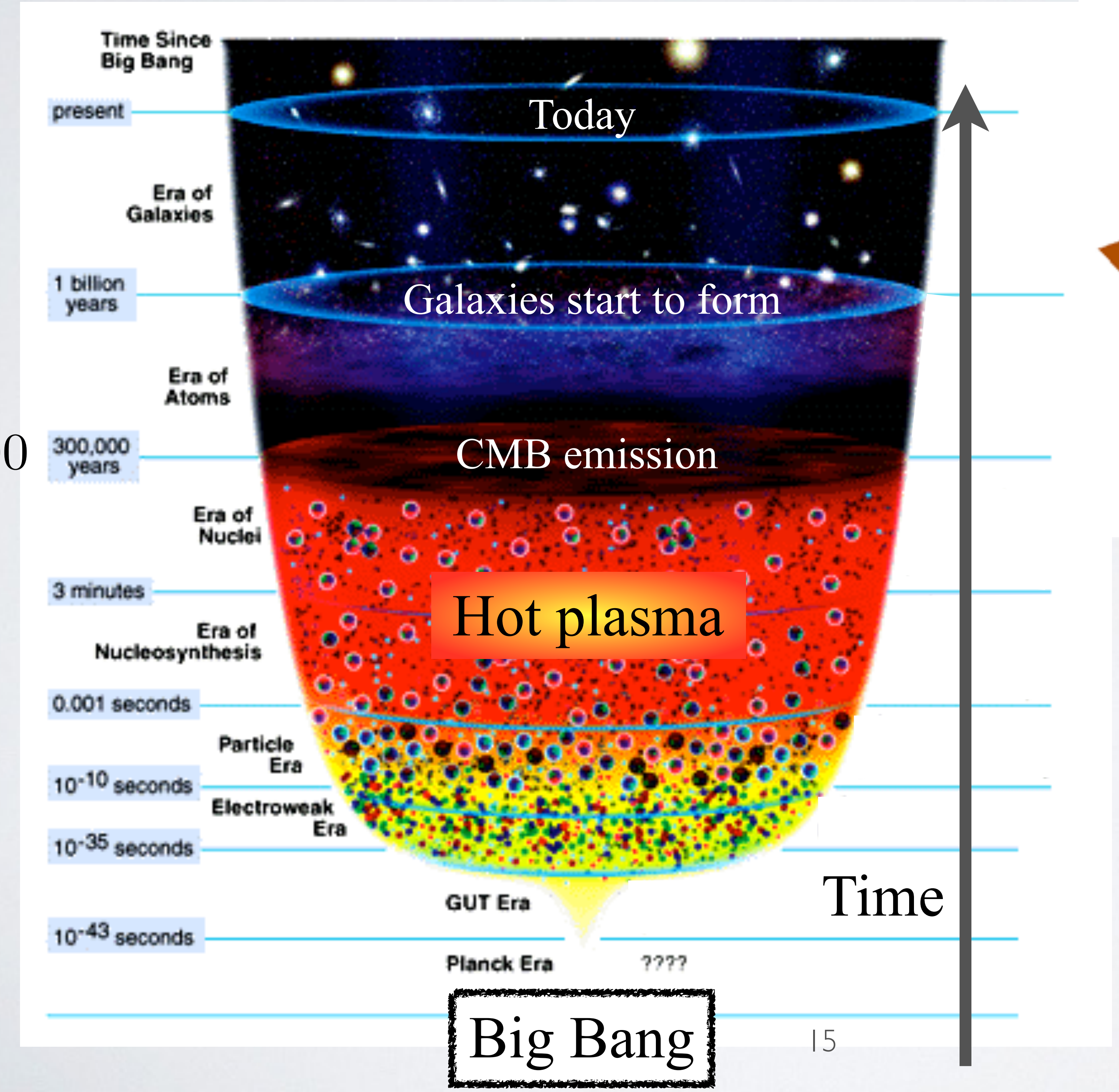
Sound wave propagation until CMB emission

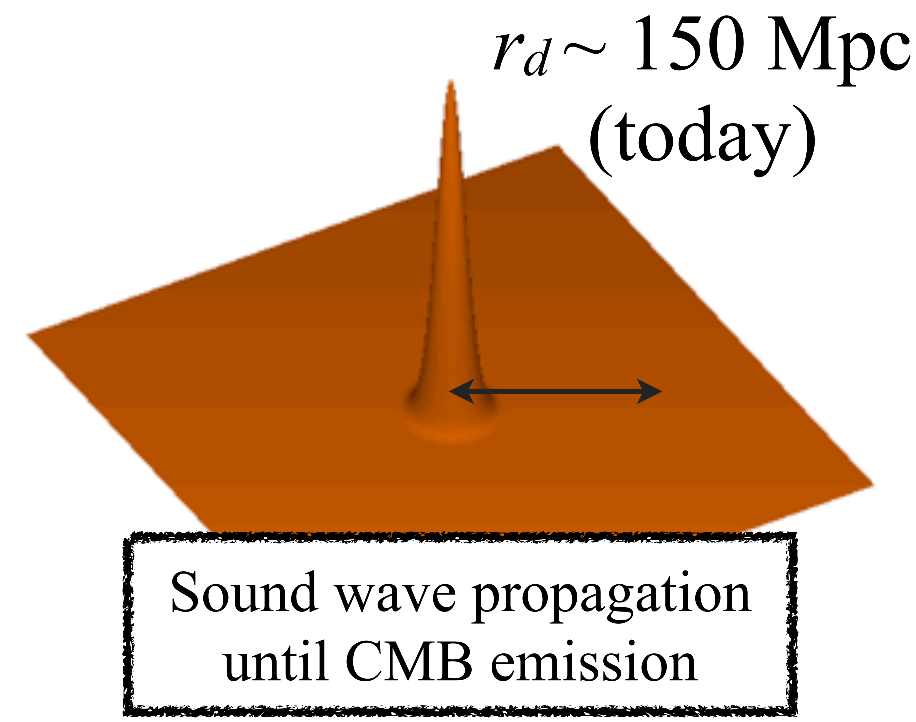
BAO

The origin of the standard ruler

$z = 0$

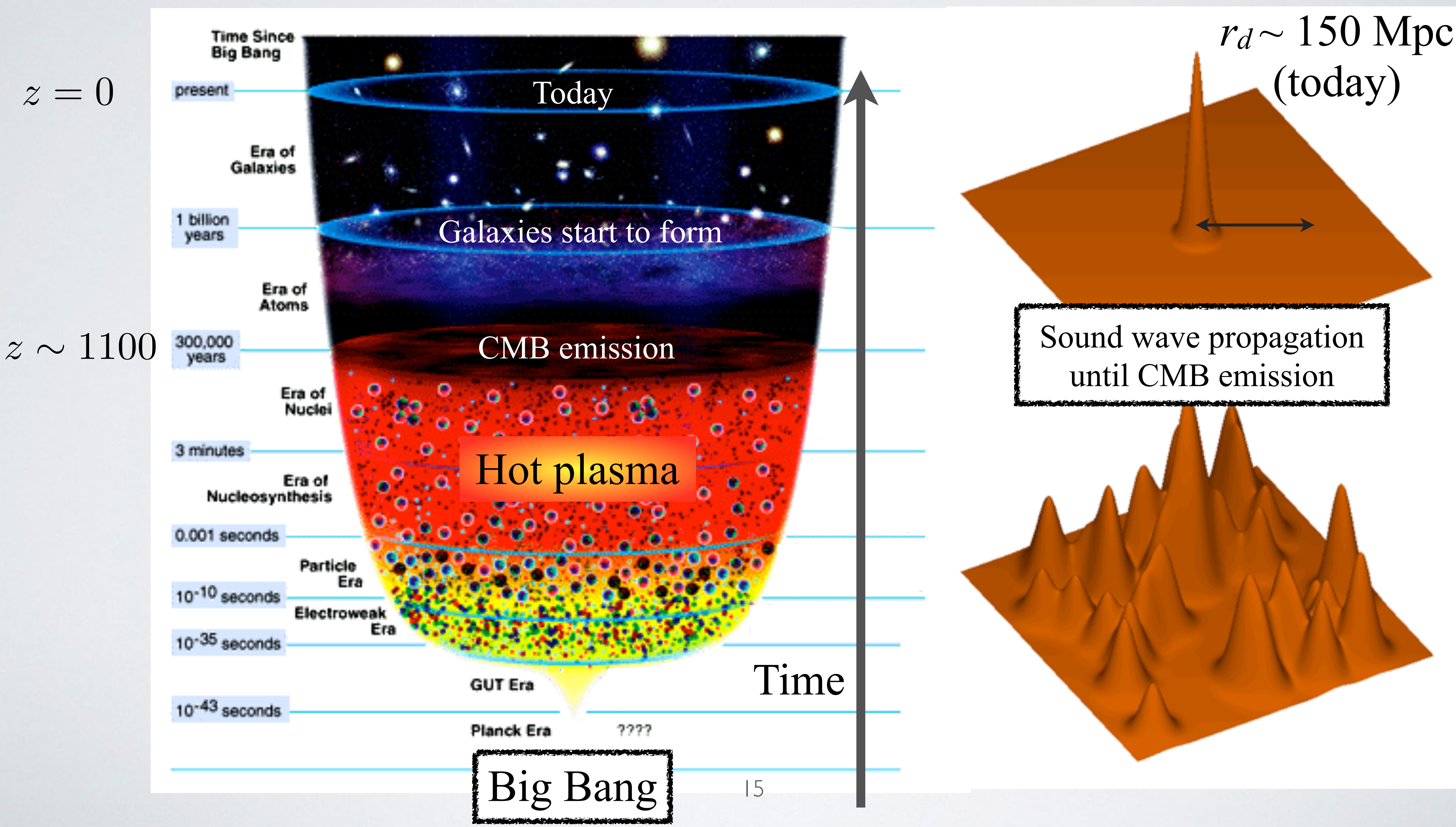
$z \sim 1100$





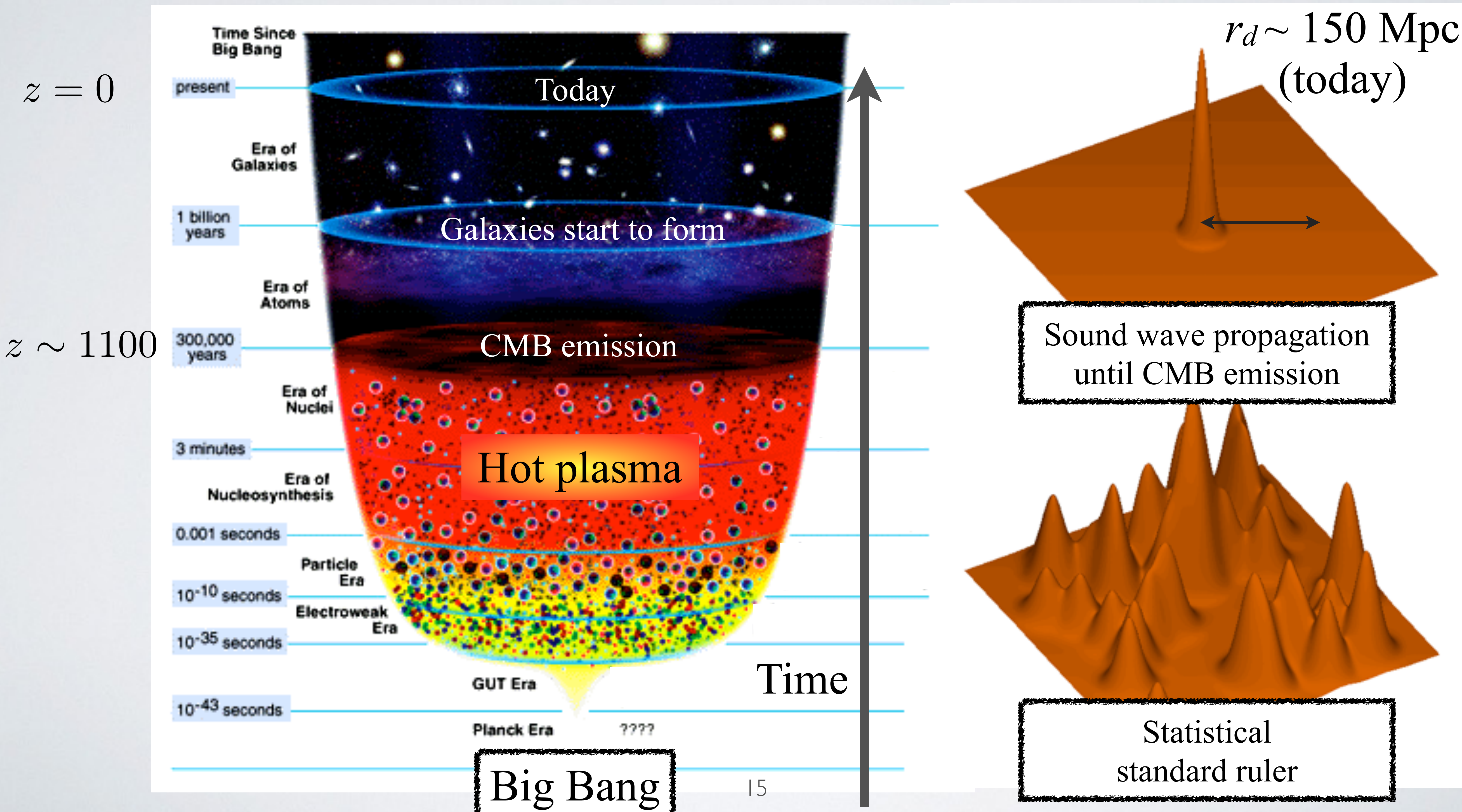
BAO

The origin of the standard ruler



BAO

The origin of the standard ruler



BAO

The origin of the standard ruler

BAO

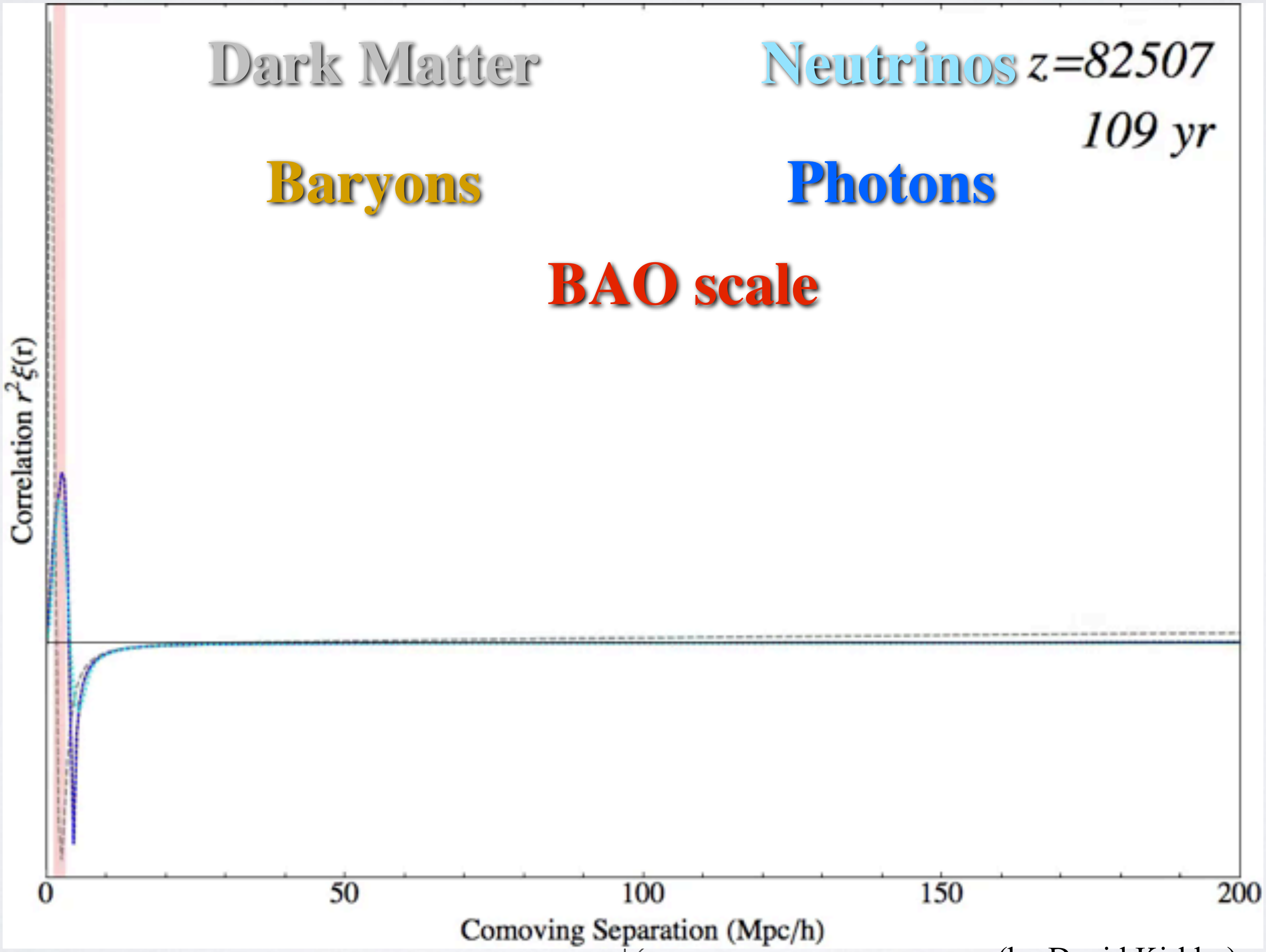
The origin of the standard ruler

Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$

BAO

The origin of the standard ruler

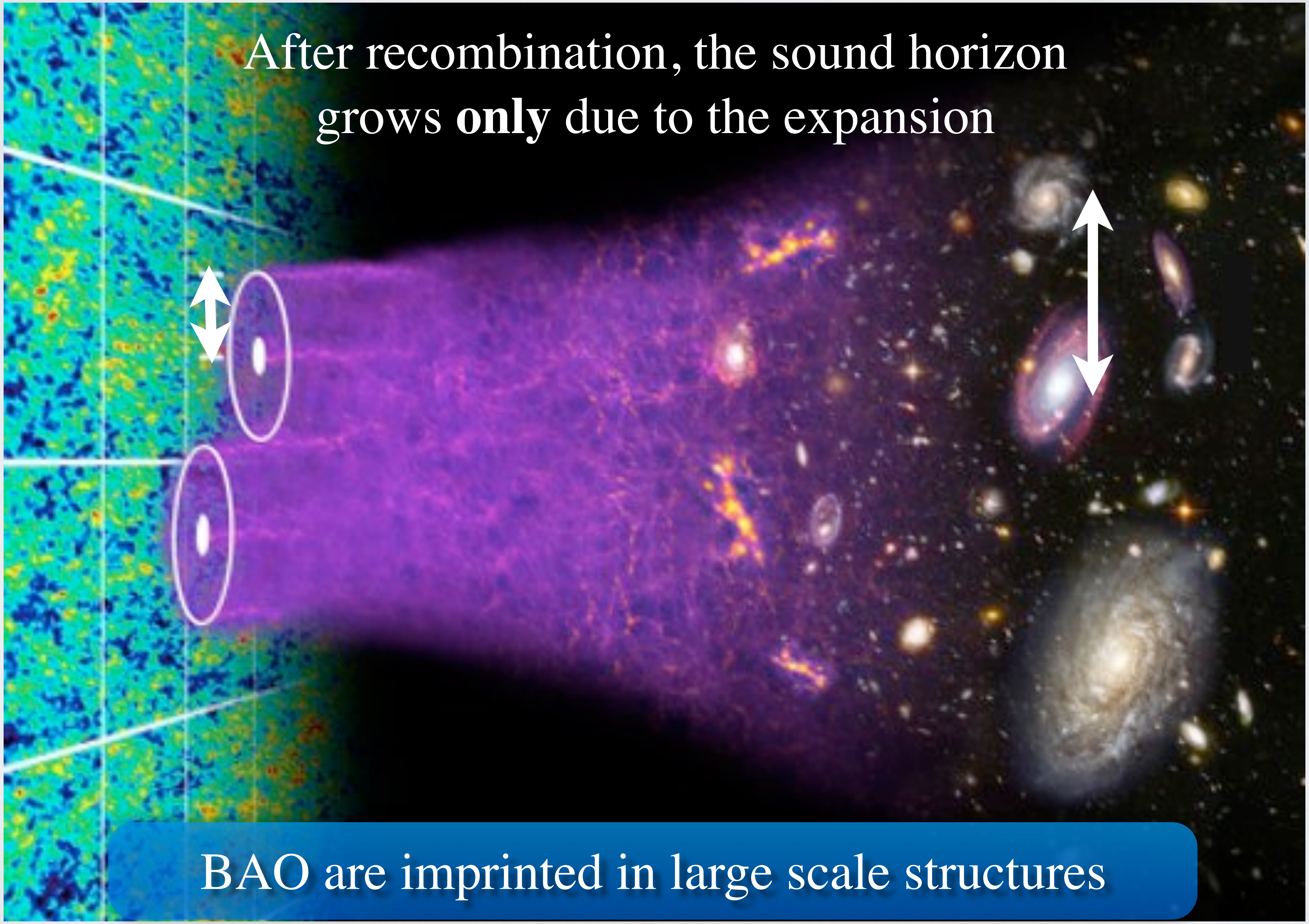
Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$



(by David Kirkby)

BAO

The origin of the standard ruler



(sdss3.org)

Measuring BAO scale

Measuring BAO scale

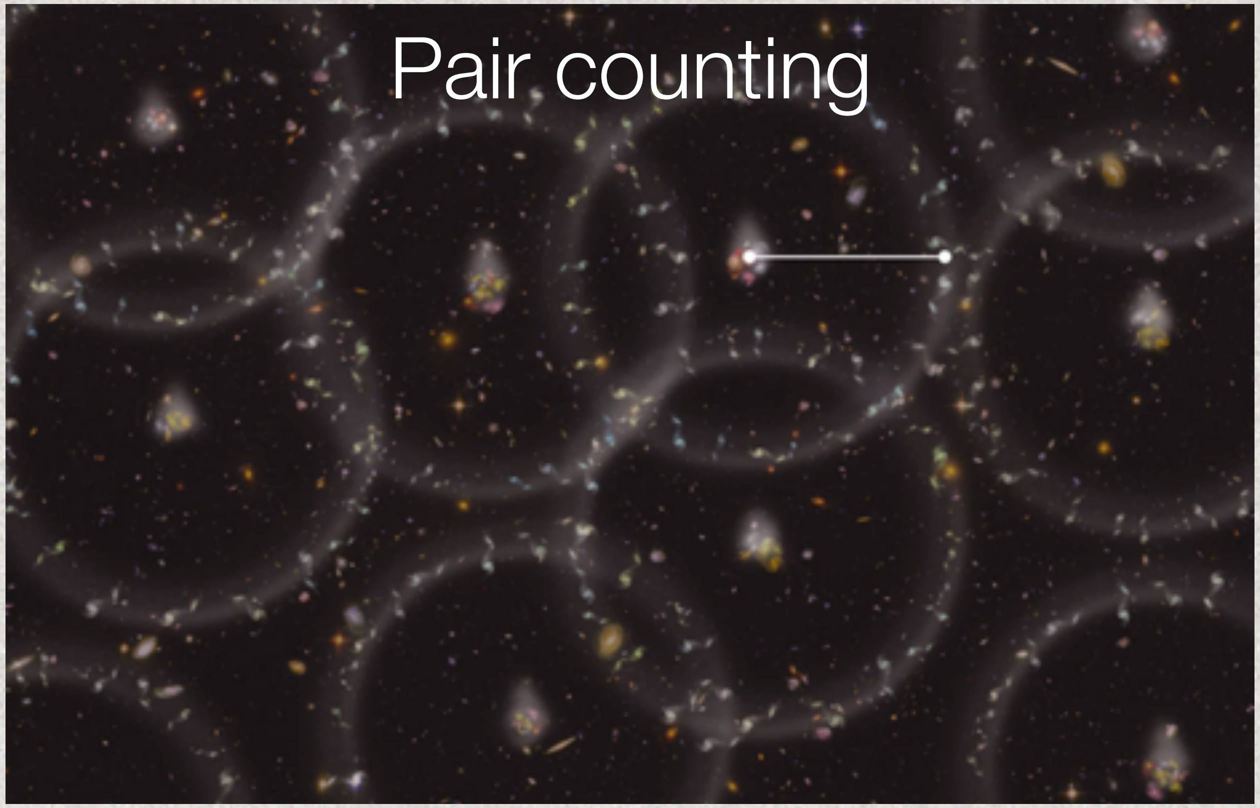
Galaxies or Quasars

Trace dense regions $\delta \gg 200$

Measuring BAO scale

Galaxies or Quasars

Trace dense regions $\delta \gg 200$

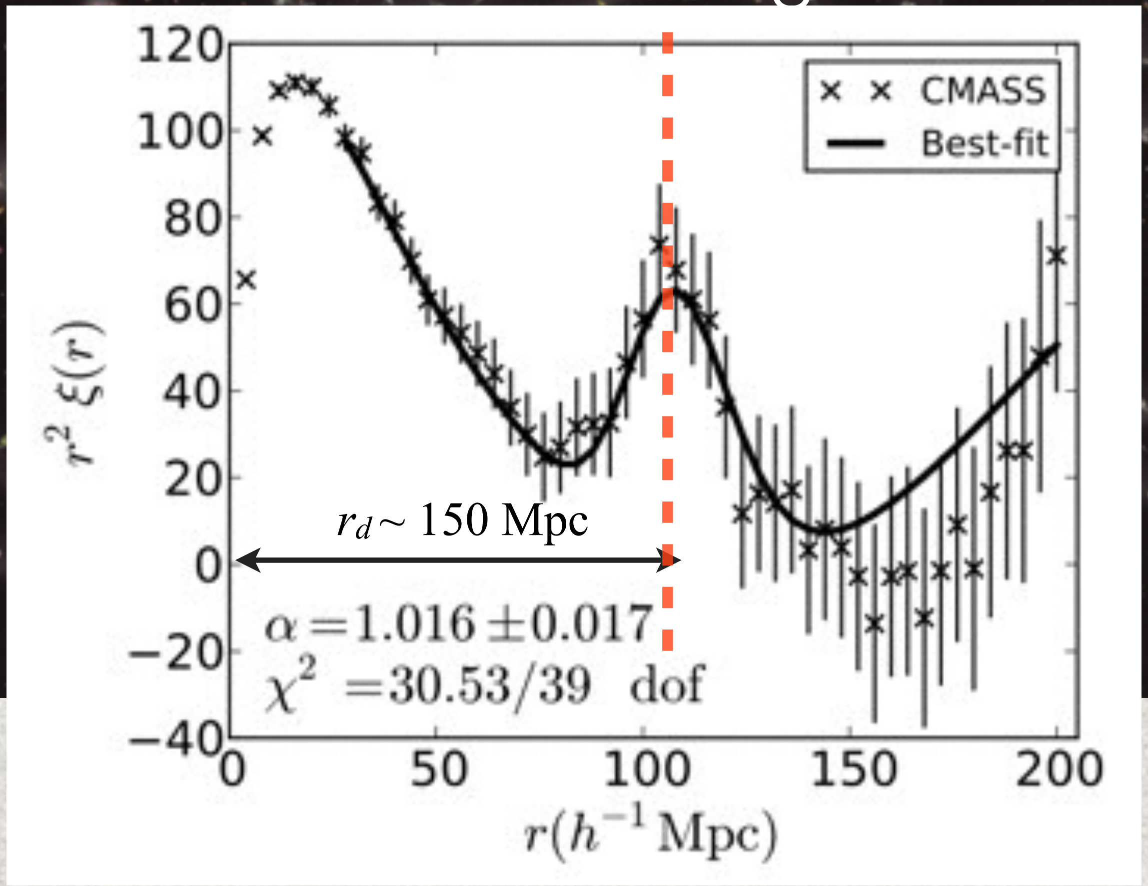


Measuring BAO scale

Galaxies or Quasars

Trace dense regions $\delta \gg 200$

BOSS galaxies $z \sim 0.57$



(Anderson et al. 2012)

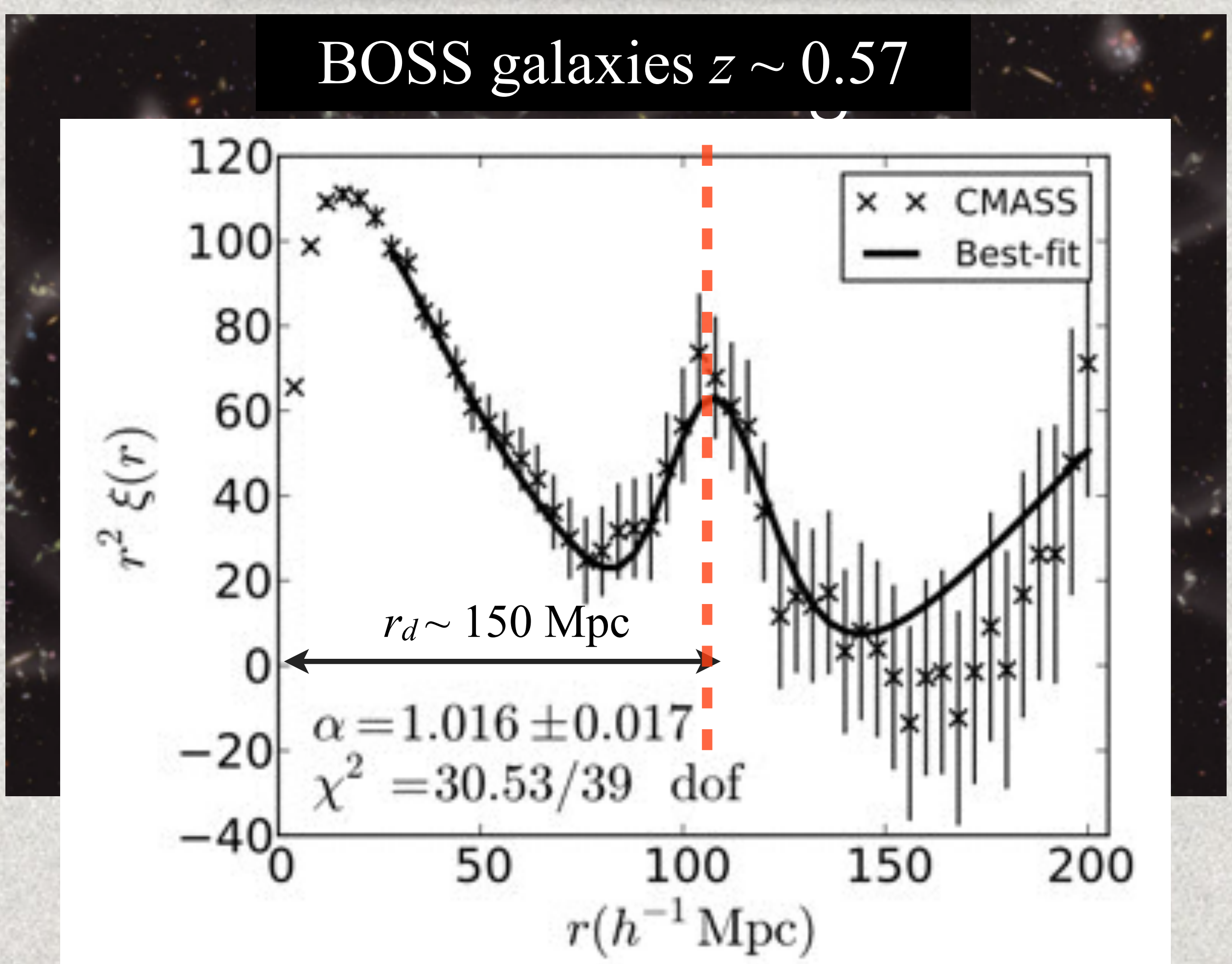
Measuring BAO scale

Galaxies or Quasars

Trace dense regions $\delta \gg 200$

Lyman-α Forest

Small over-densities $\delta \approx 1$



(Anderson et al. 2012)

Measuring BAO scale

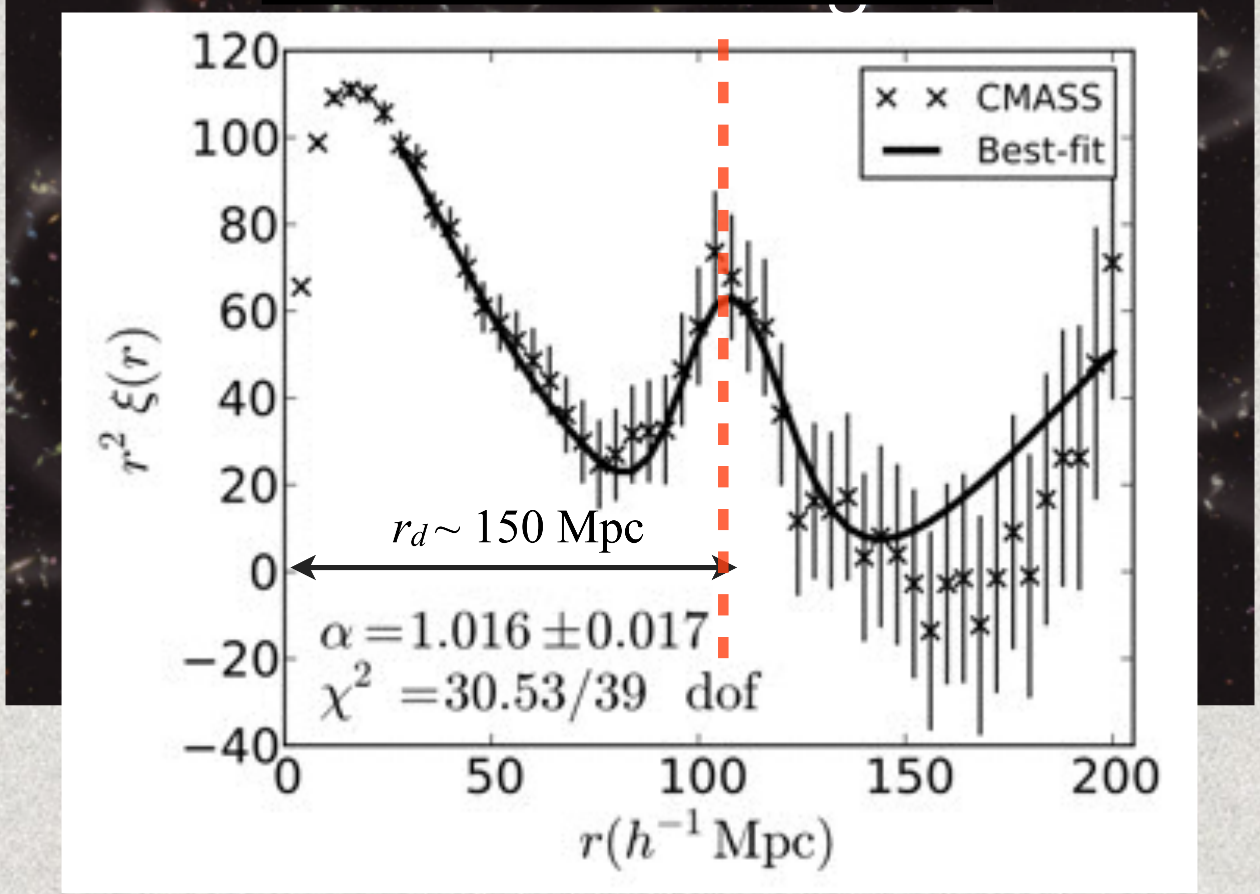
Galaxies or Quasars

Trace dense regions $\delta \gg 200$

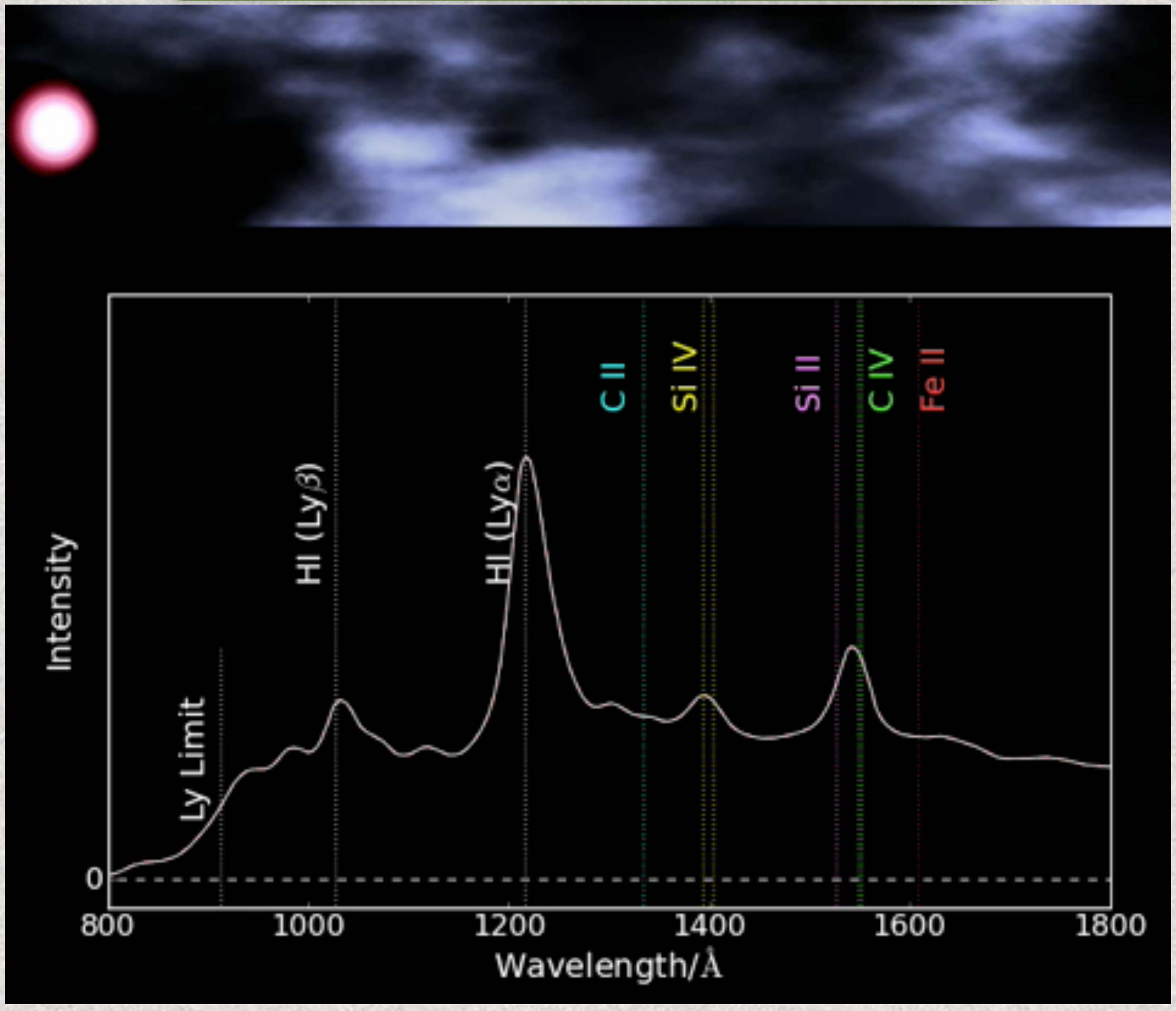
Lyman-α Forest

Small over-densities $\delta \approx 1$

BOSS galaxies $z \sim 0.57$



(Anderson et al. 2012)



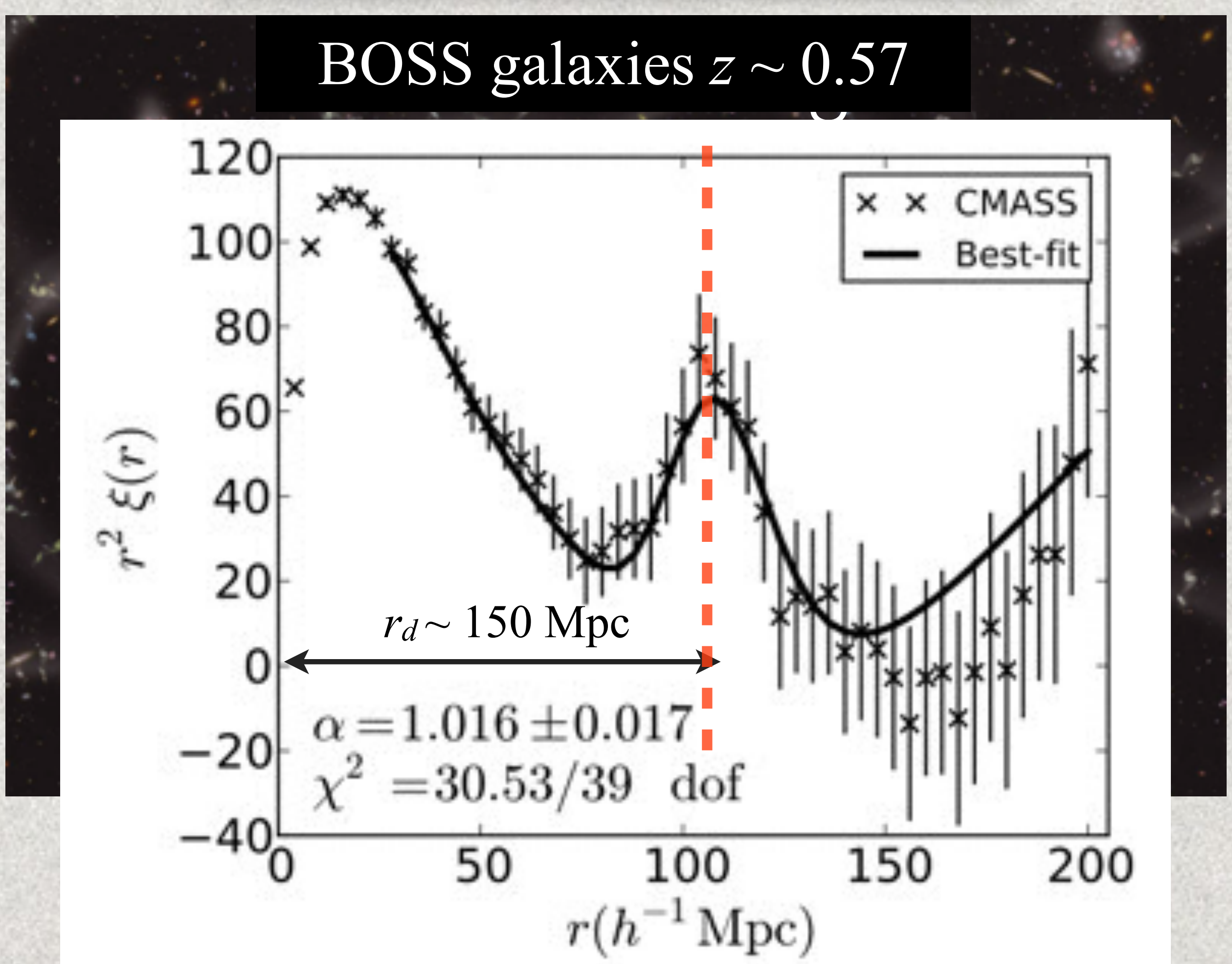
Measuring BAO scale

Galaxies or Quasars

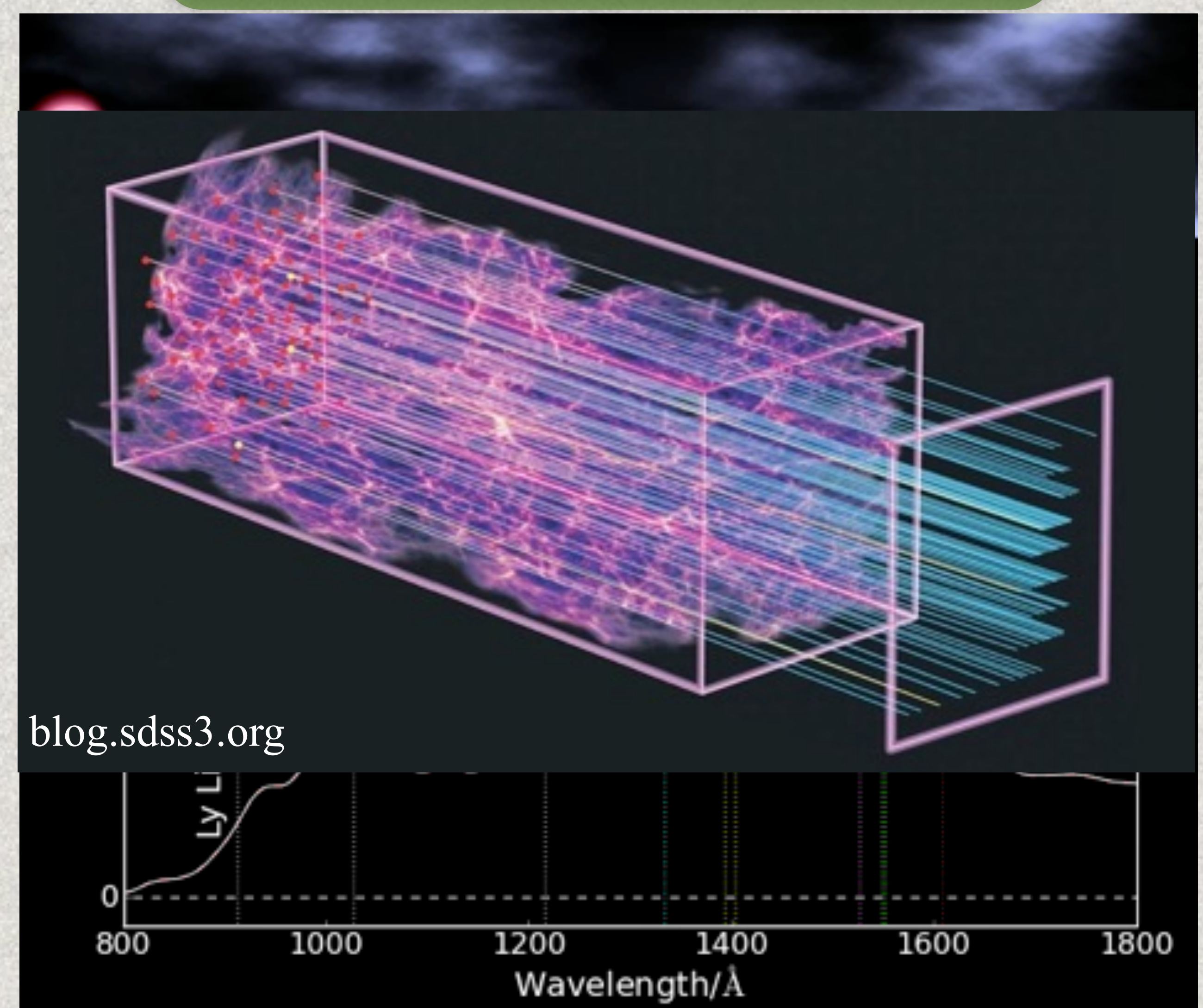
Trace dense regions $\delta \gg 200$

Lyman-α Forest

Small over-densities $\delta \approx 1$

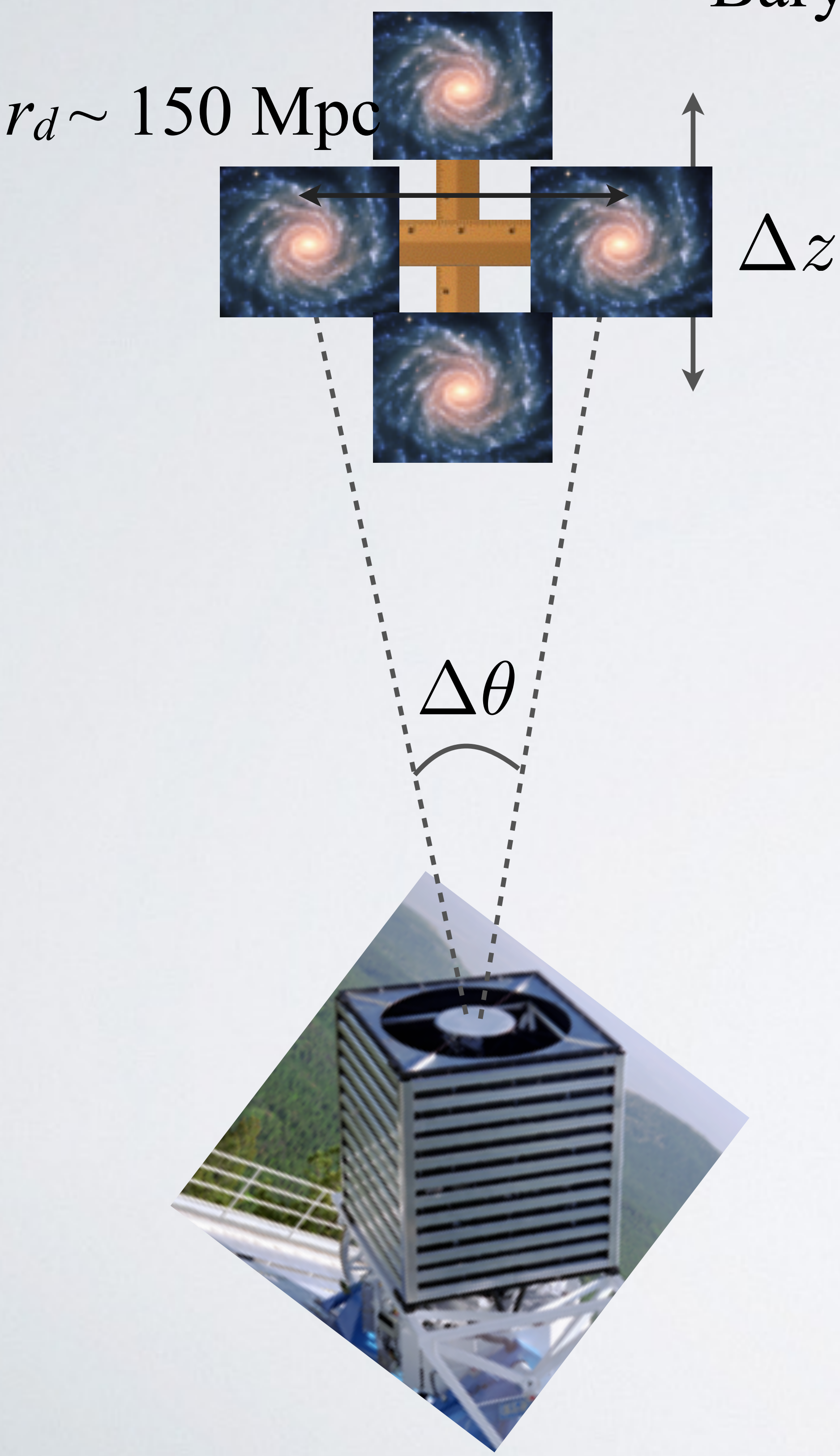


(Anderson et al. 2012)



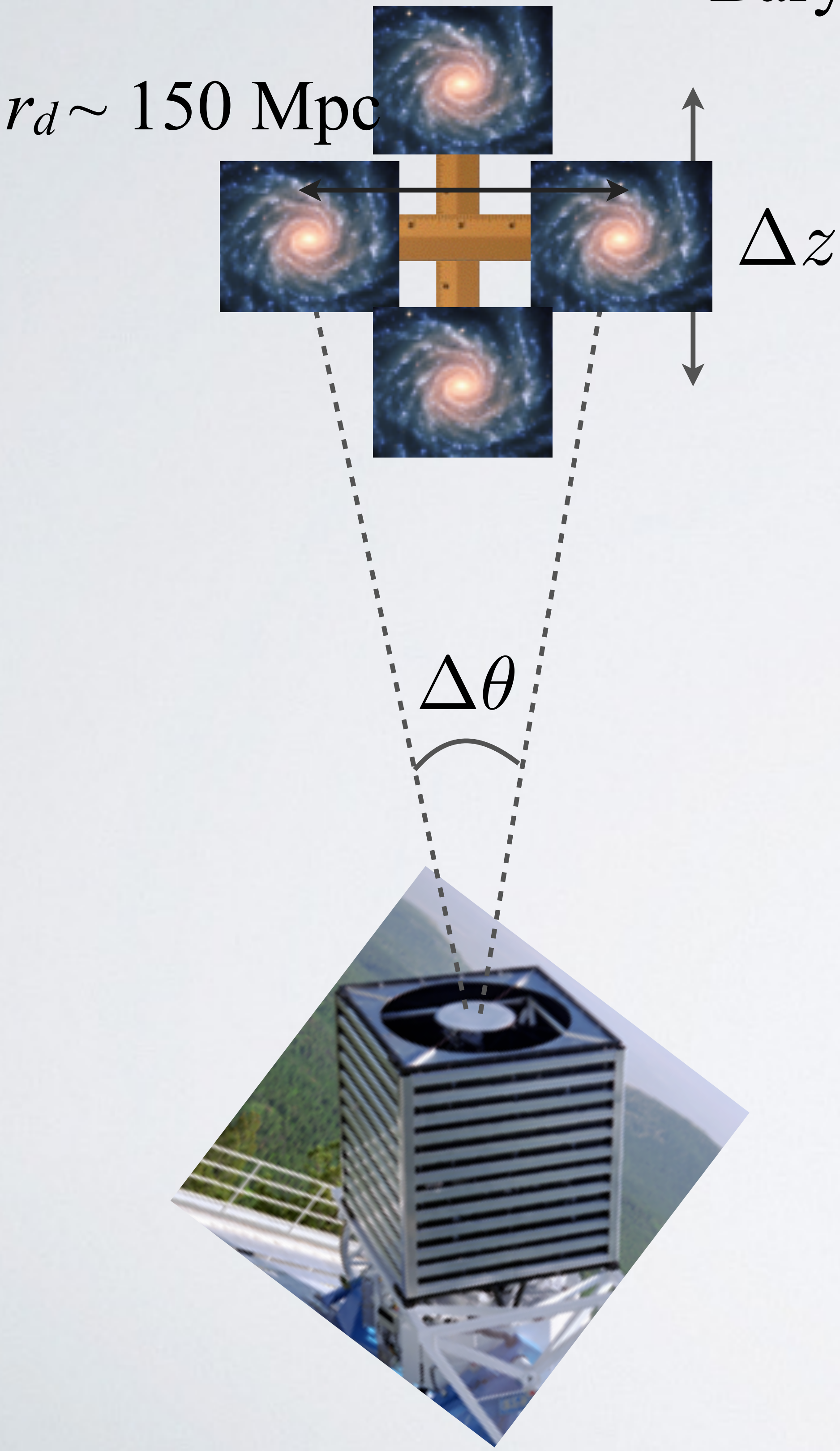
BAO

Baryon Acoustic Oscillations



BAO

Baryon Acoustic Oscillations

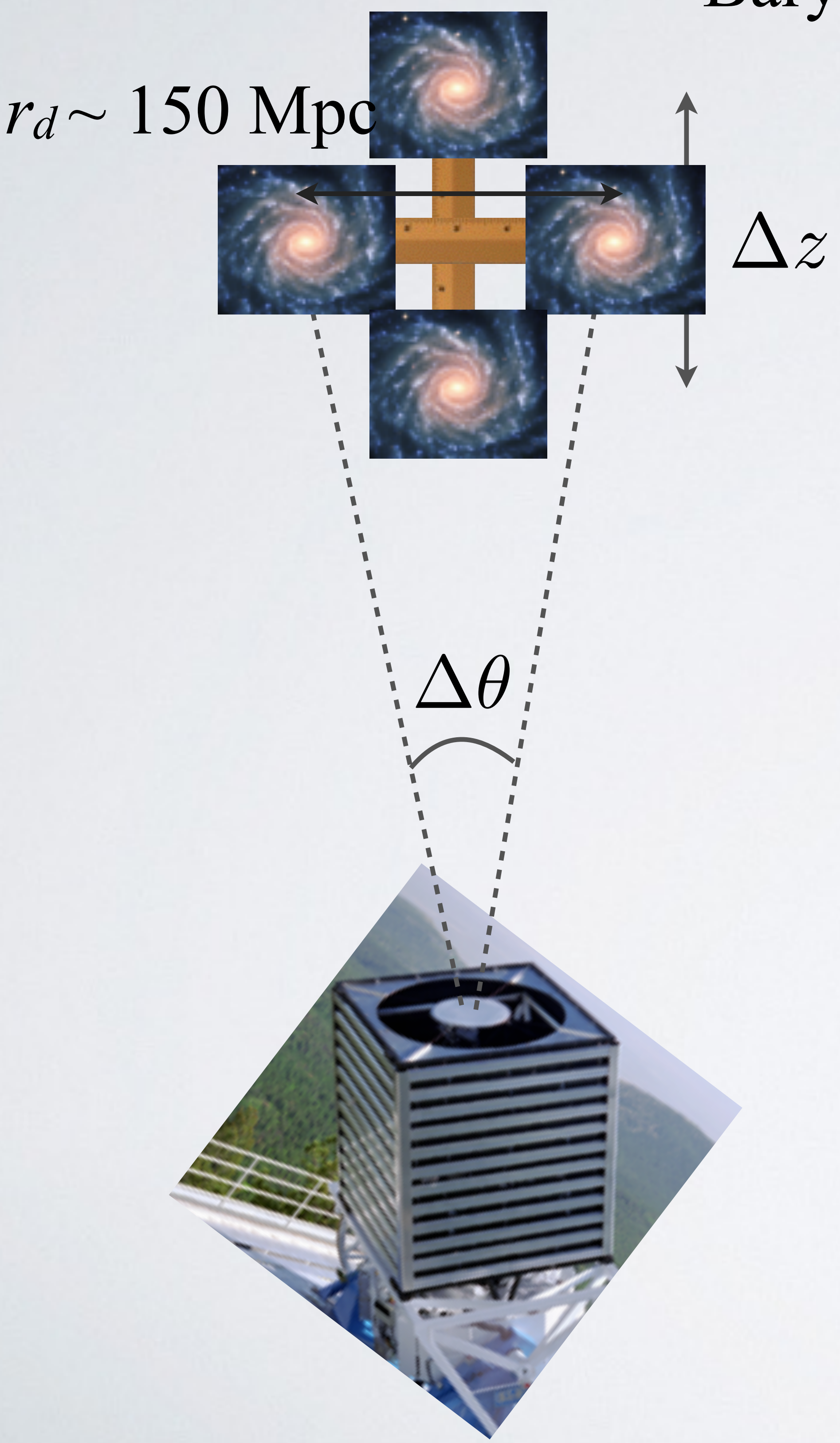


Distances

$$\Delta\theta \propto \frac{r_d}{D_A(z)}$$

BAO

Baryon Acoustic Oscillations



Distances

$$\Delta\theta \propto \frac{r_d}{D_A(z)}$$

Hubble's law (in the past)

$$\Delta z \propto \frac{r_d}{D_H(z)}$$

$$\left(D_H(z) = \frac{c}{H(z)} \right)$$

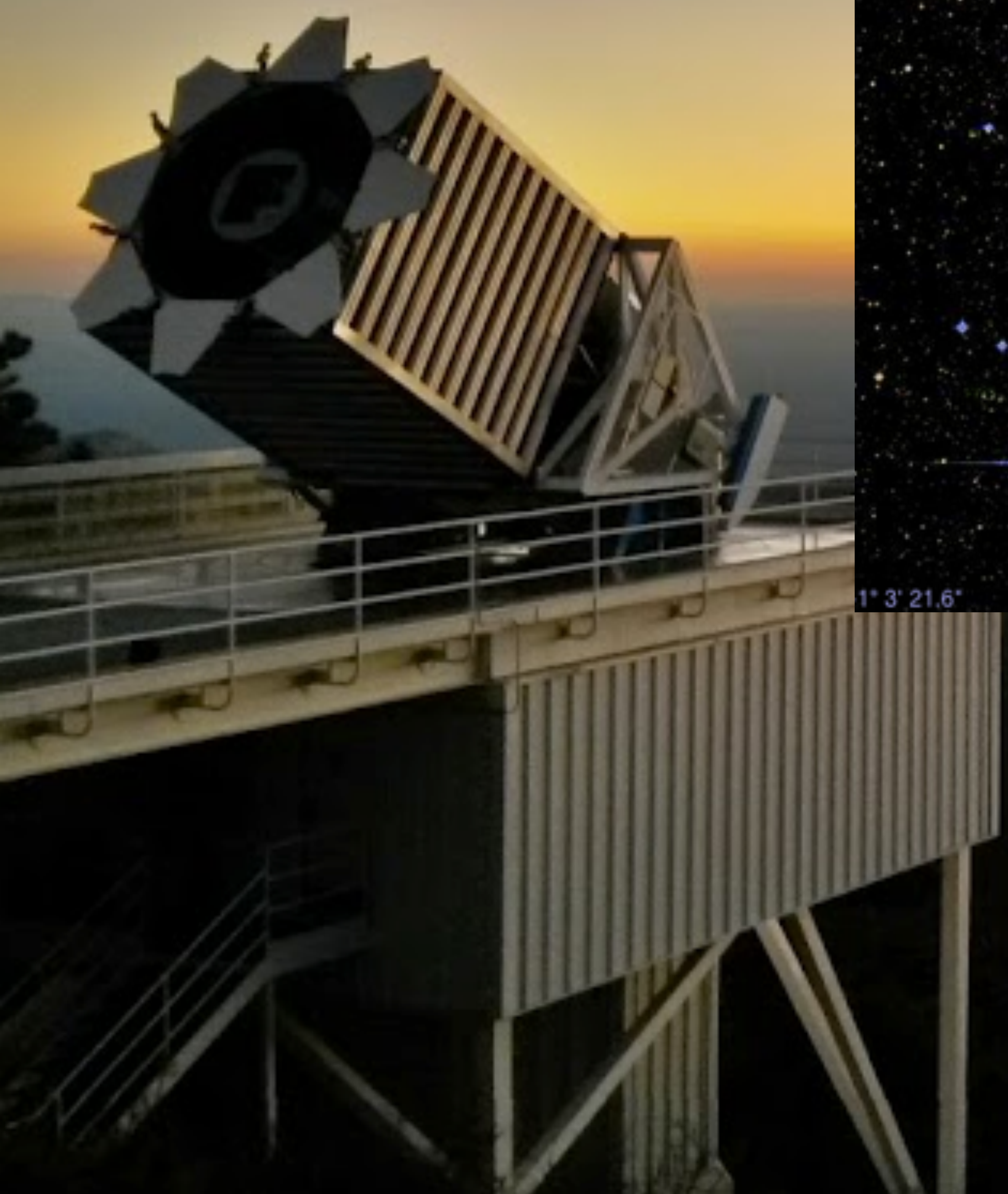
BOSS

Baryon Oscillation Spectroscopic Survey


BOSS
Baryon Oscillation Spectroscopic Survey
Apache Point Observatory, New Mexico, USA

BOSS

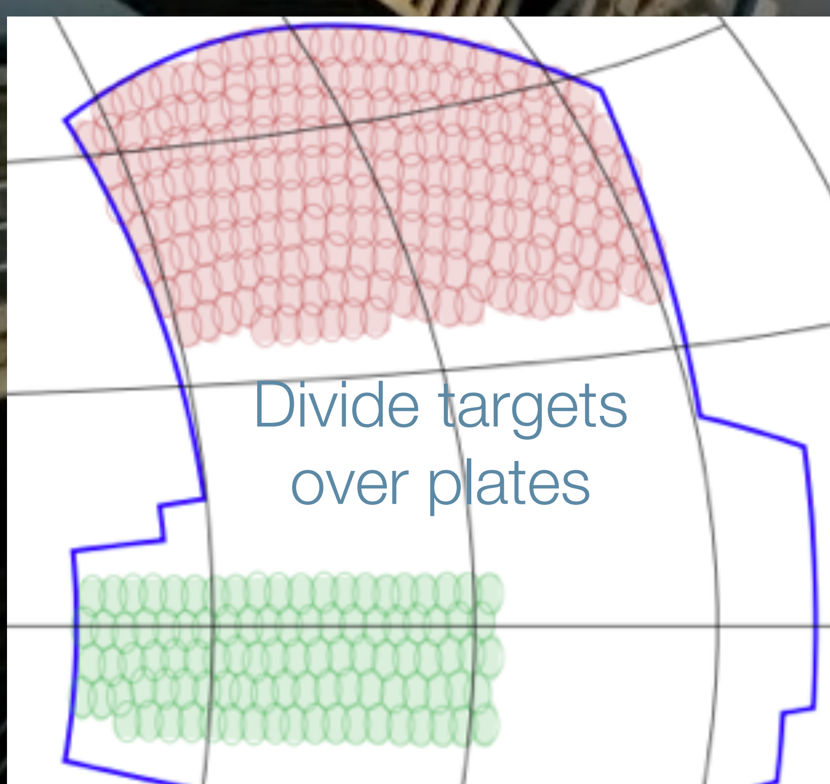
Baryon Oscillation Spectroscopic Survey



Apache Point Observatory, New Mexico, USA

BOSS

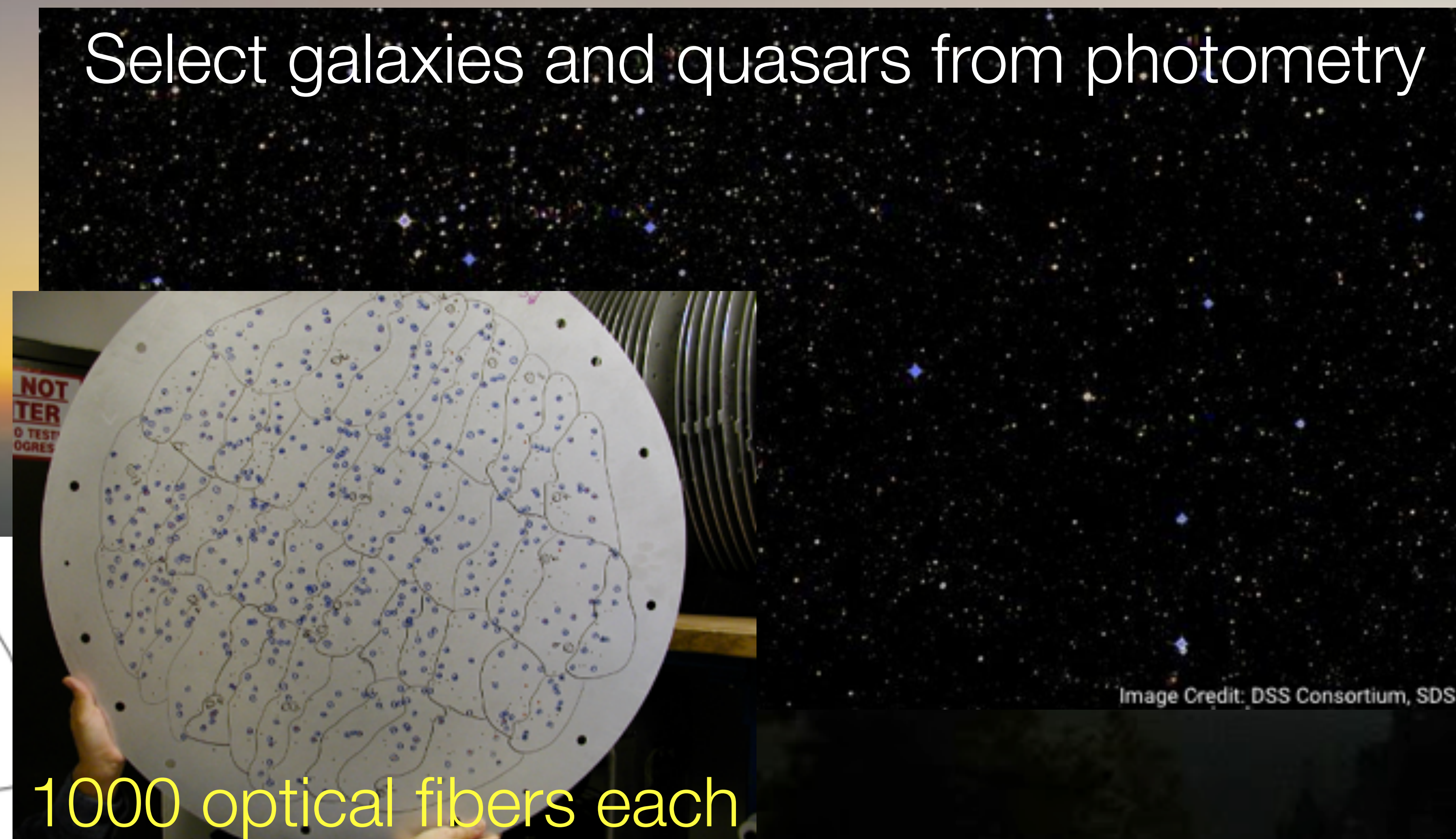
Baryon Oscillation Spectroscopic Survey

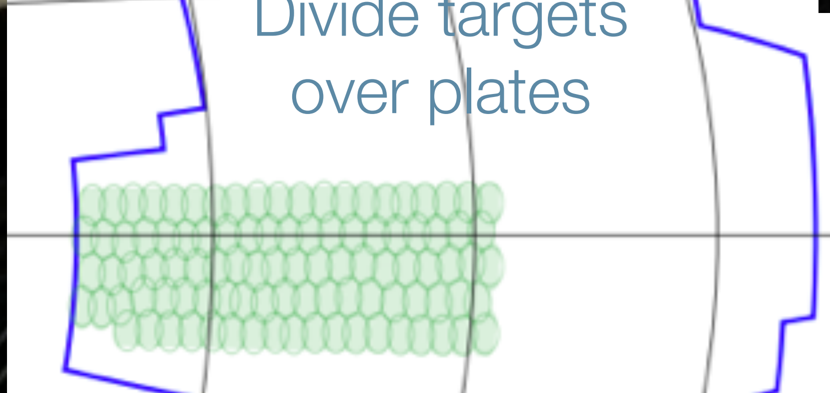


Apache Point Observatory, New Mexico, USA

BOSS

Baryon Oscillation Spectroscopic Survey

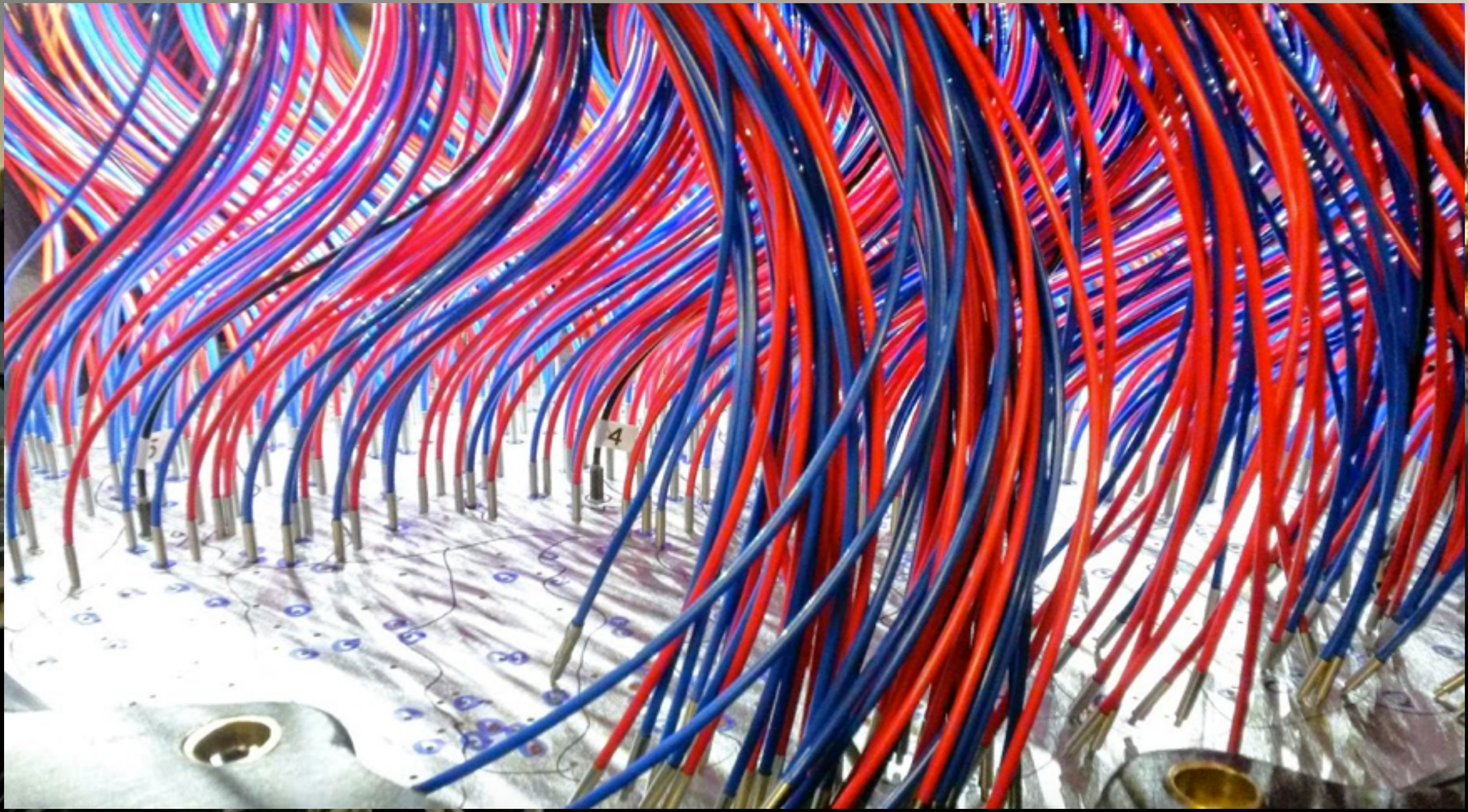




Apache Point Observatory, New Mexico, USA

BOSS

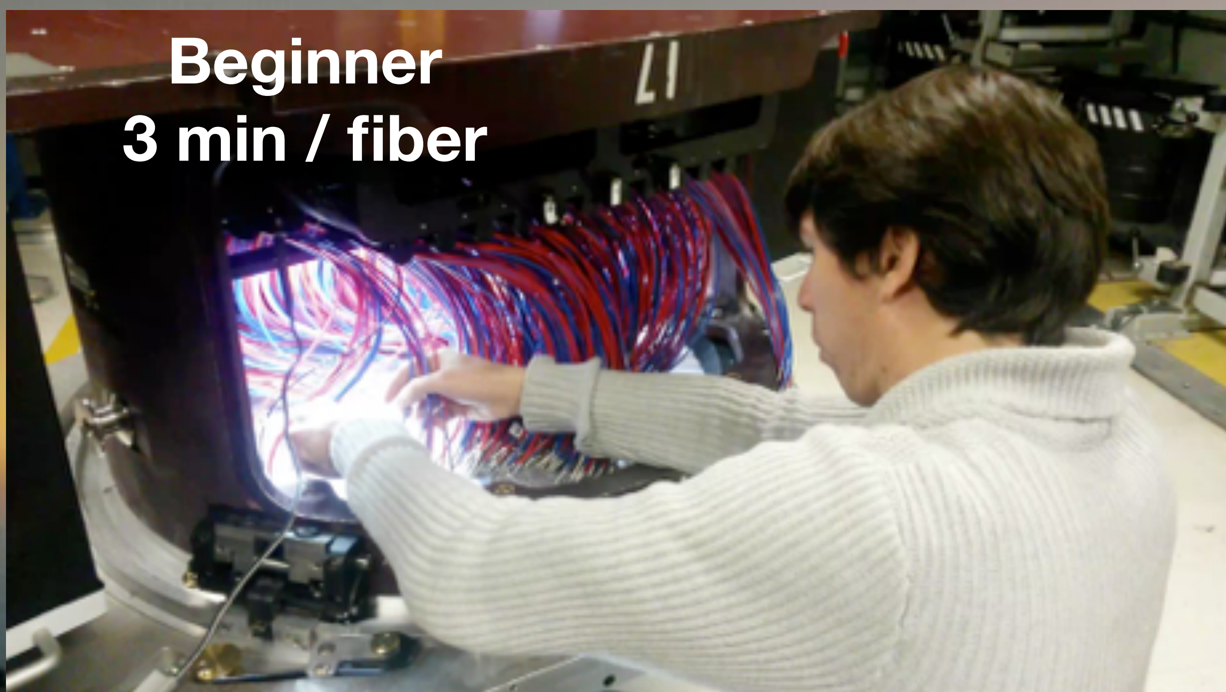
Baryon Oscillation Spectroscopic Survey

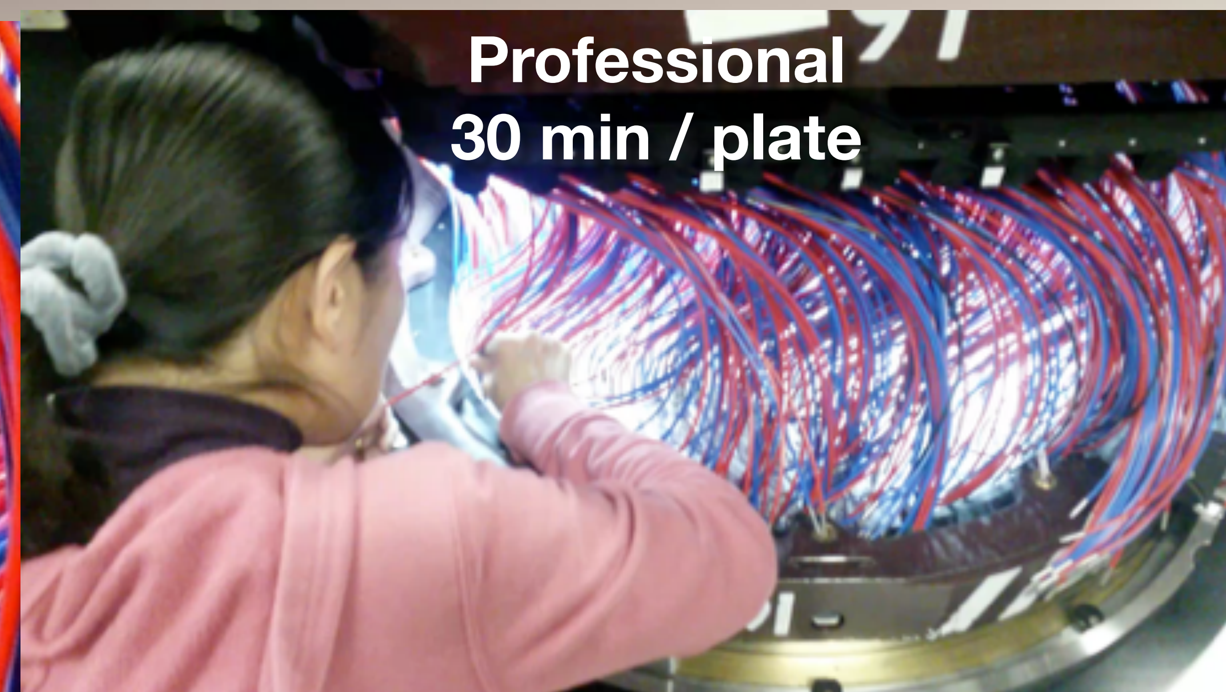


Apache Point Observatory, New Mexico, USA

BOSS

Baryon Oscillation Spectroscopic Survey

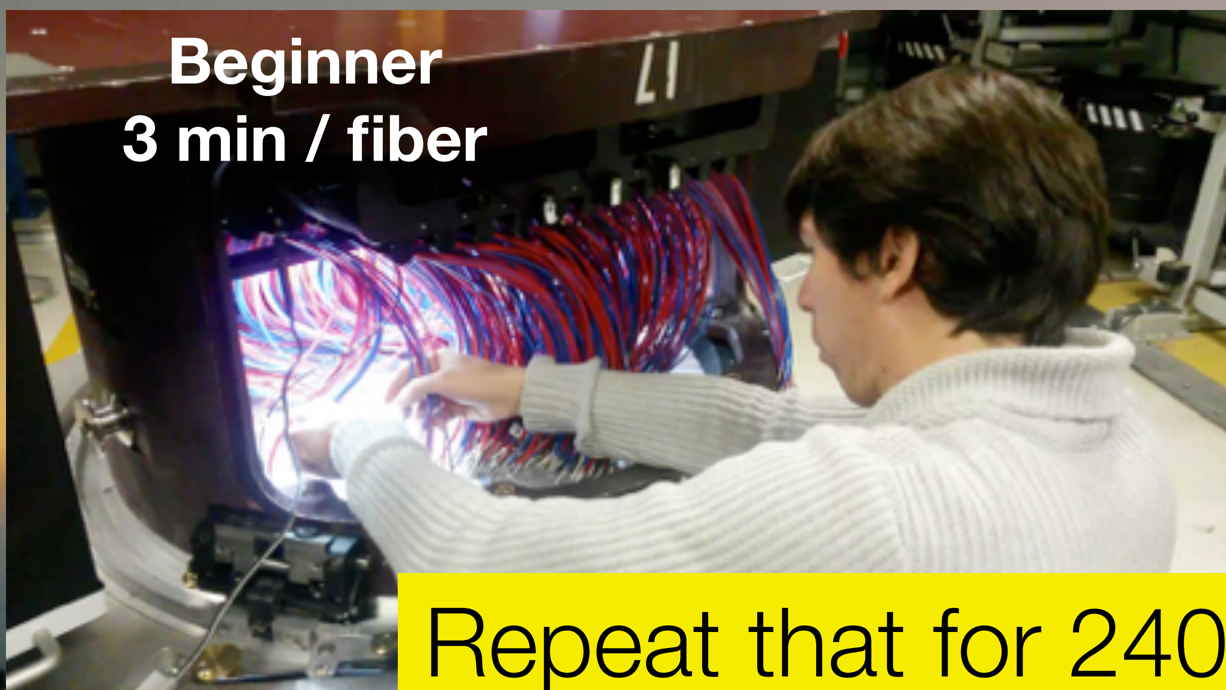


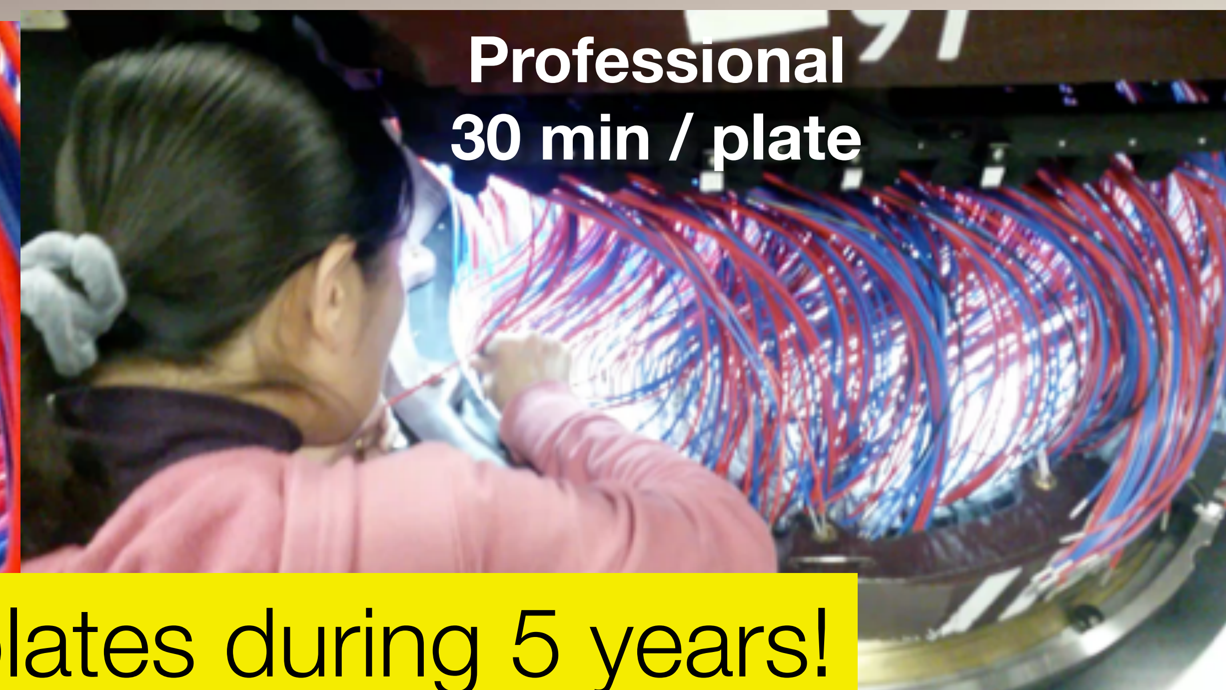


Apache Point Observatory, New Mexico, USA

BOSS

Baryon Oscillation Spectroscopic Survey





Repeat that for 2400 plates during 5 years!

Apache Point Observatory, New Mexico, USA

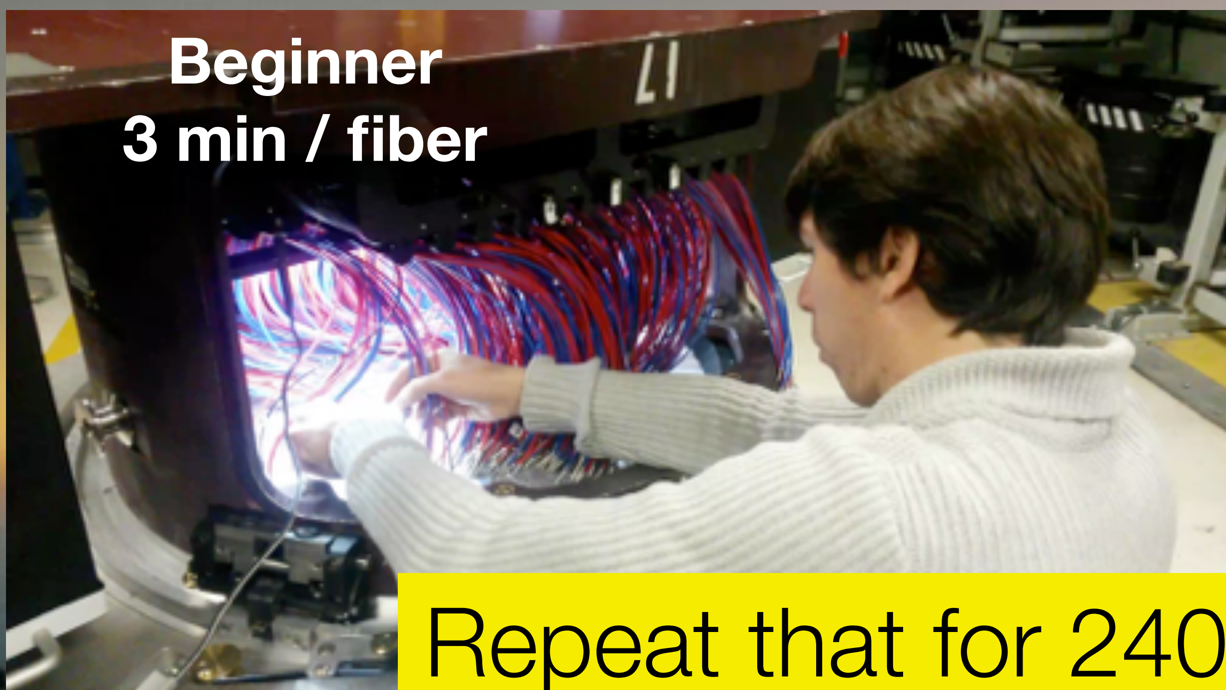
BOSS

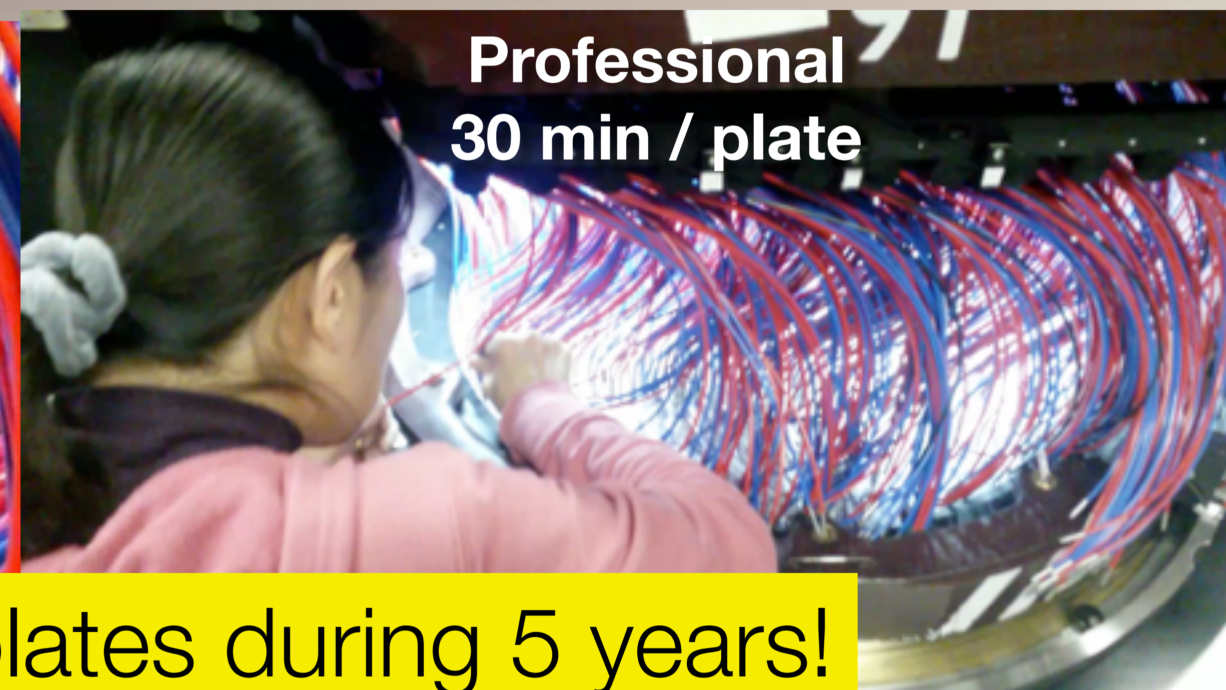
Baryon Oscillation Spectroscopic Survey

Apache Point Observatory, New Mexico, USA

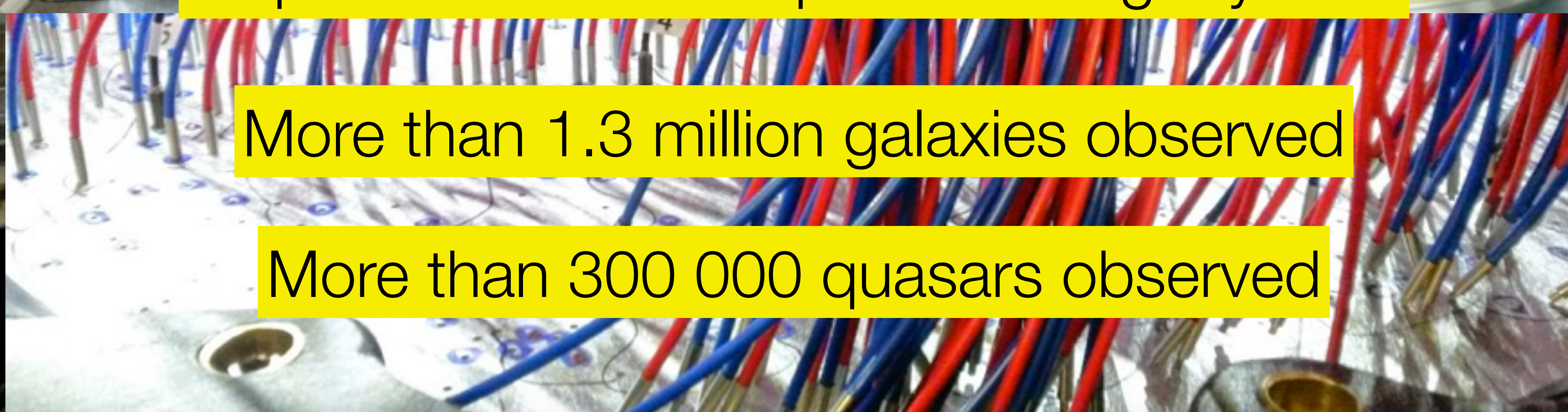
BOSS

Baryon Oscillation Spectroscopic Survey





Repeat that for 2400 plates during 5 years!



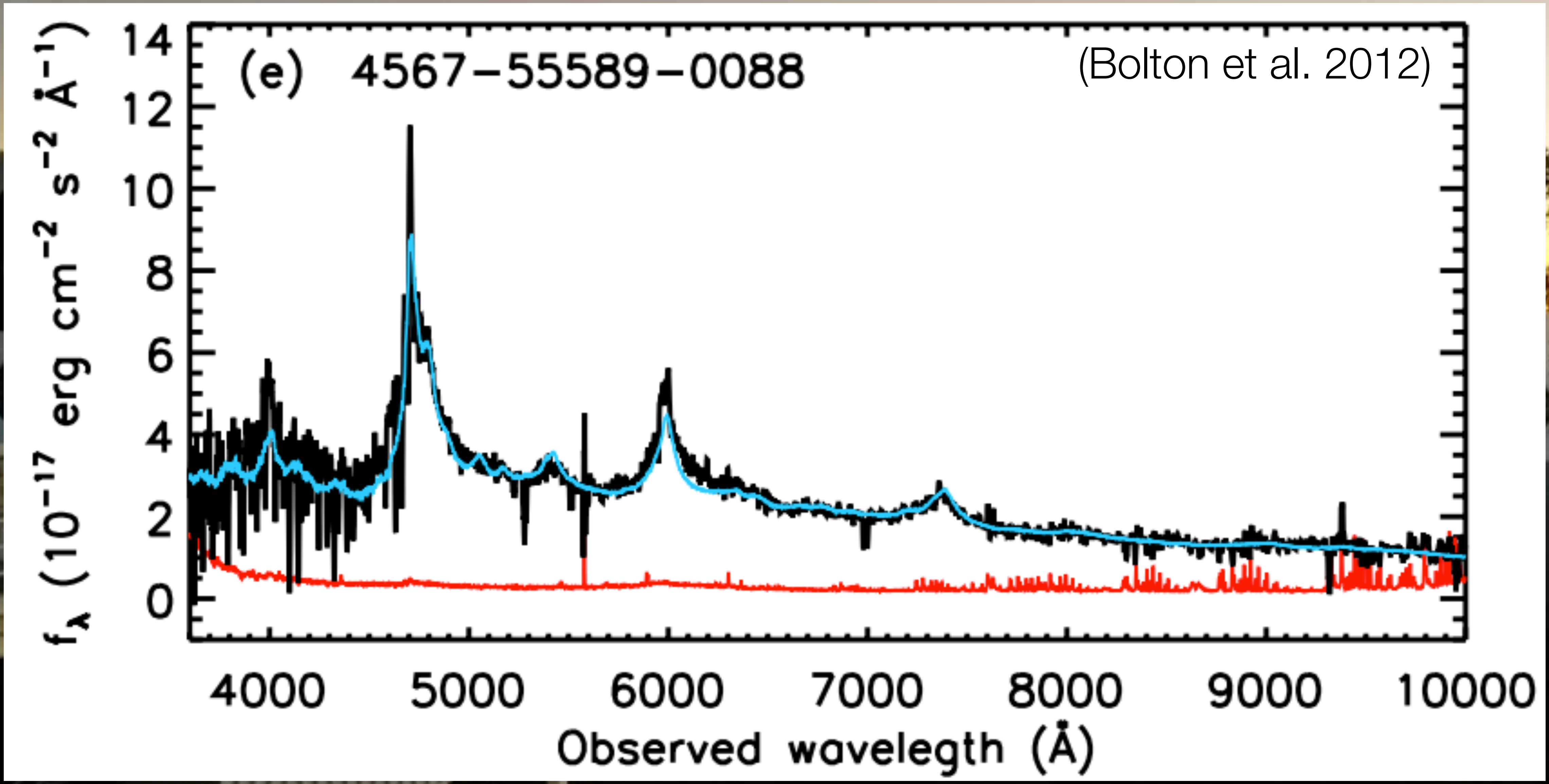
More than 1.3 million galaxies observed

More than 300 000 quasars observed

Apache Point Observatory, New Mexico, USA

BOSS

Baryon Oscillation Spectroscopic Survey



Apache Point Observatory, New Mexico, USA

OUTLINE

Part I

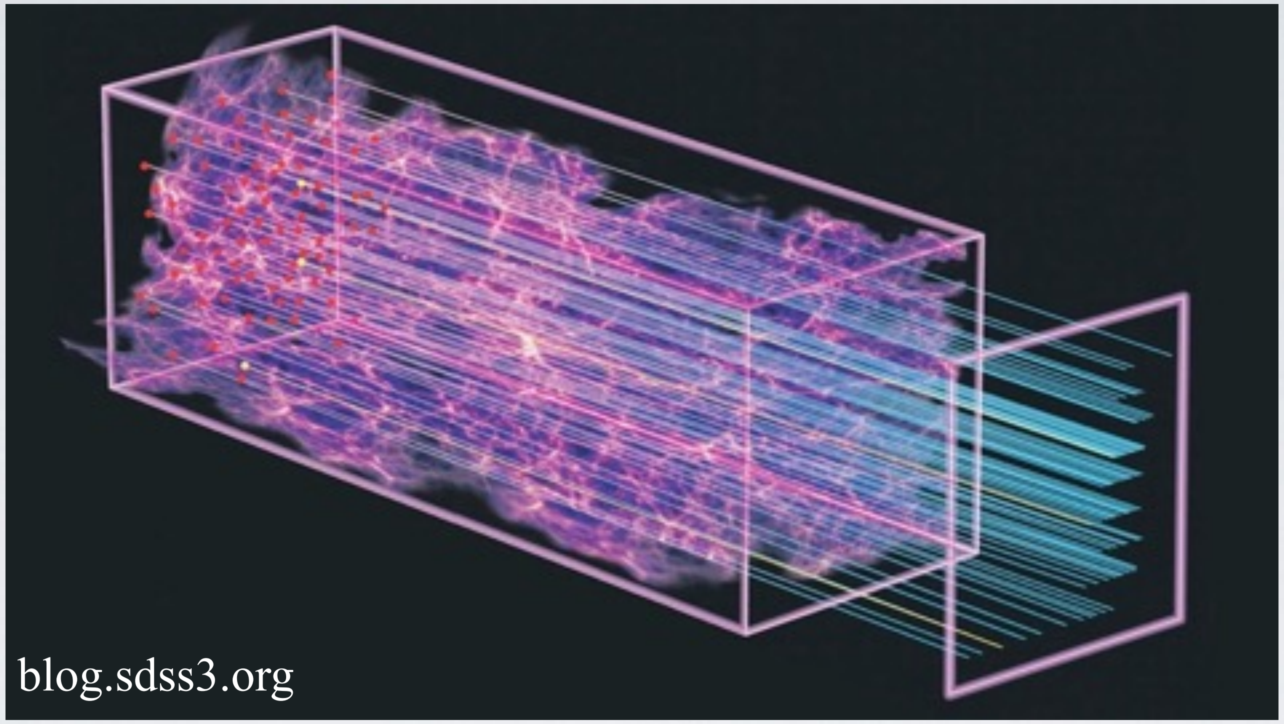
- Expansion of the Universe
- Baryon Acoustic Oscillations
- The BOSS survey

Part II

- Measuring the flux correlation function
- Results on data
- Cosmological implications
- Future

PART II

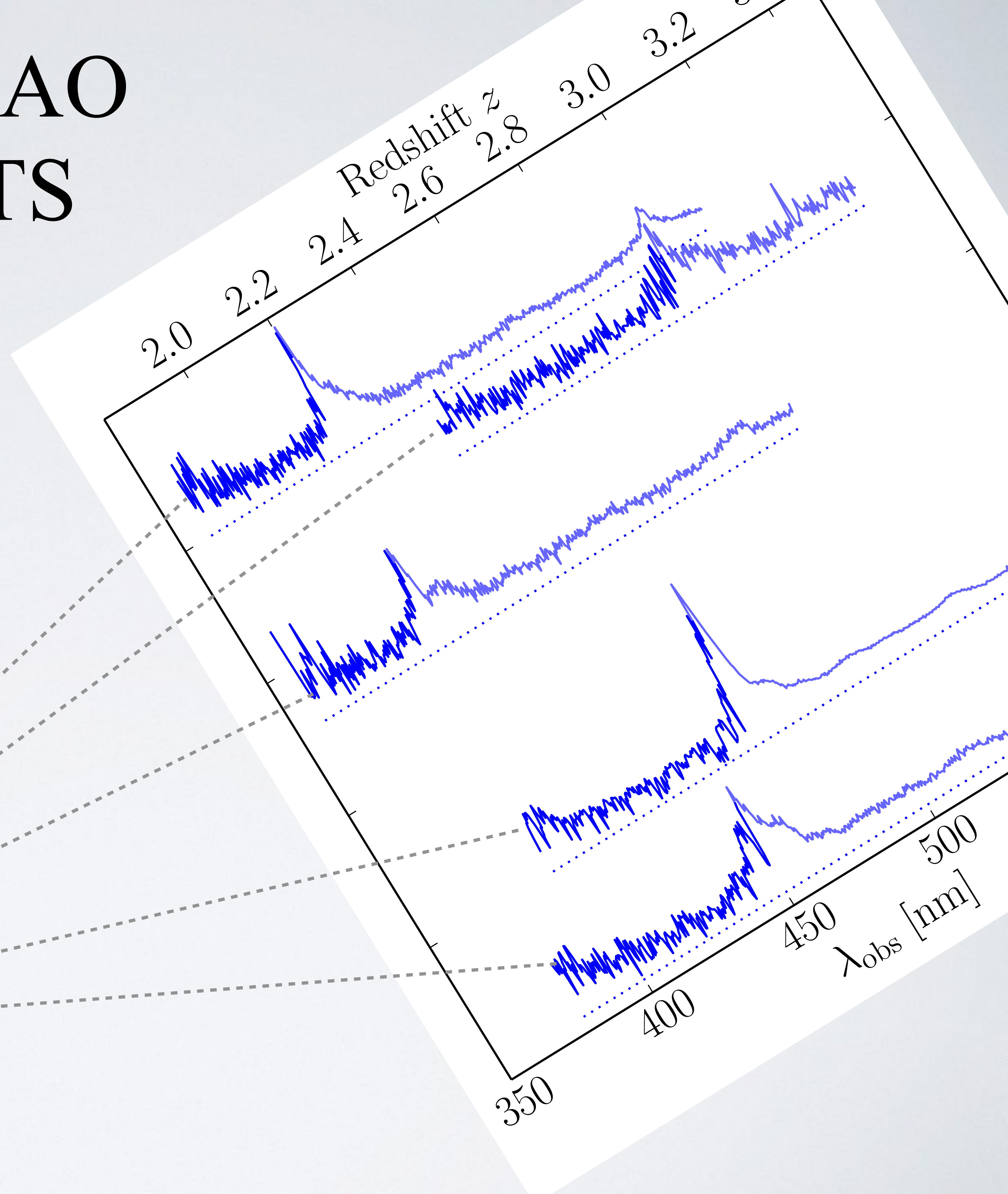
Methods, results
and cosmology



MEASURING BAO WITH FORESTS

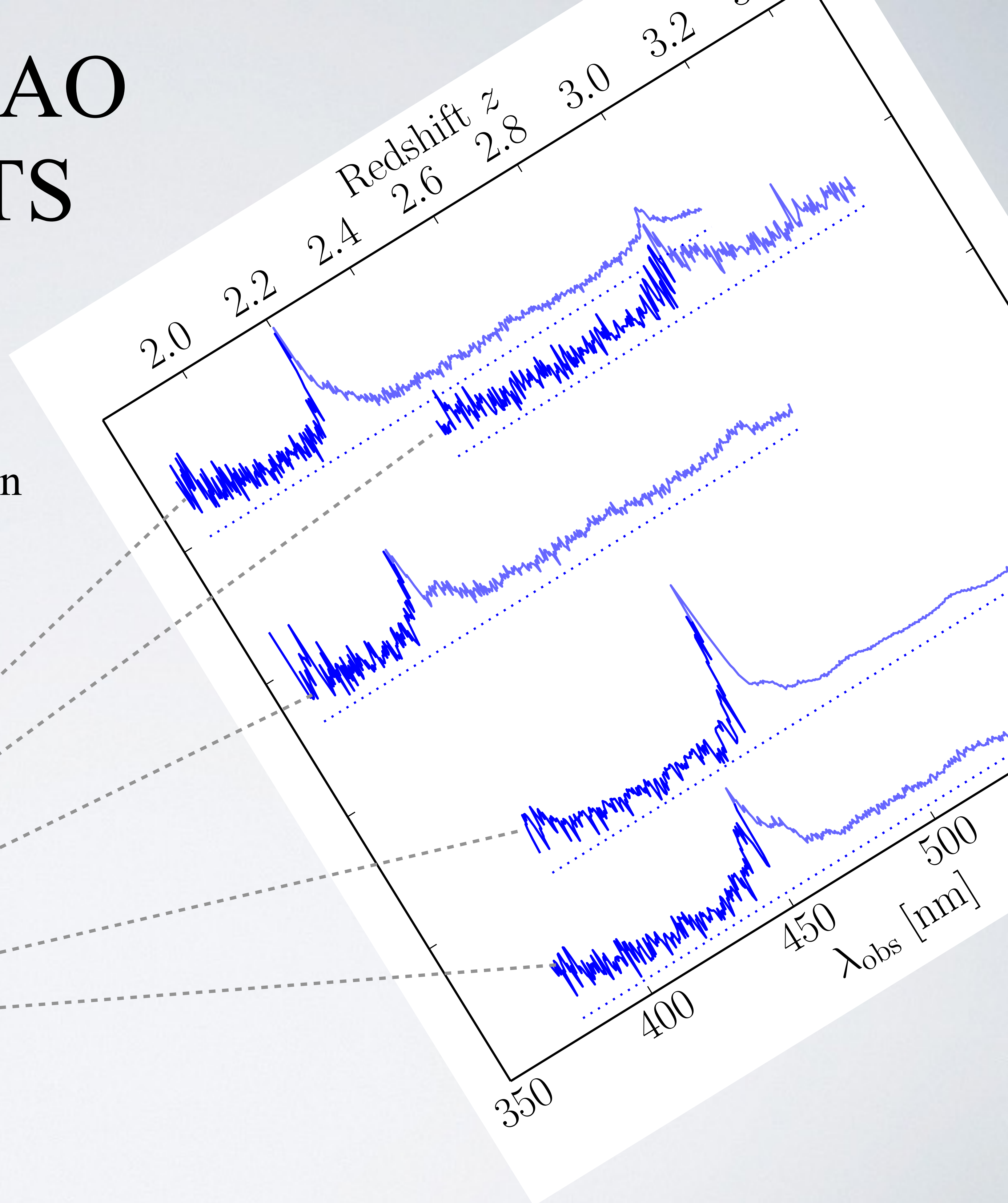
Busca et al. 2013
Slosar et al. 2013
Kirkby et al. 2013
Font-Ribera et al. 2013
Delubac, JB, et al. 2014
JB et al. 2017
Du Mas des Bourboux et al. 2017

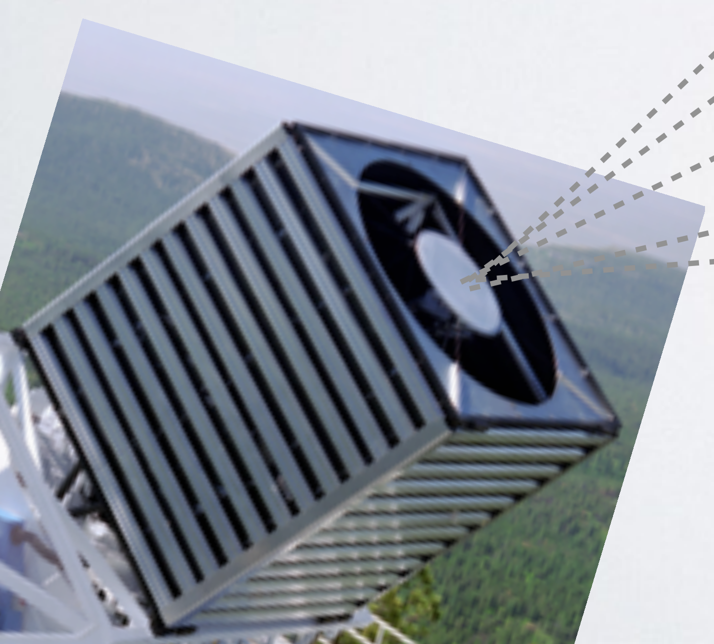
MEASURING BAO WITH FORESTS



MEASURING BAO WITH FORESTS

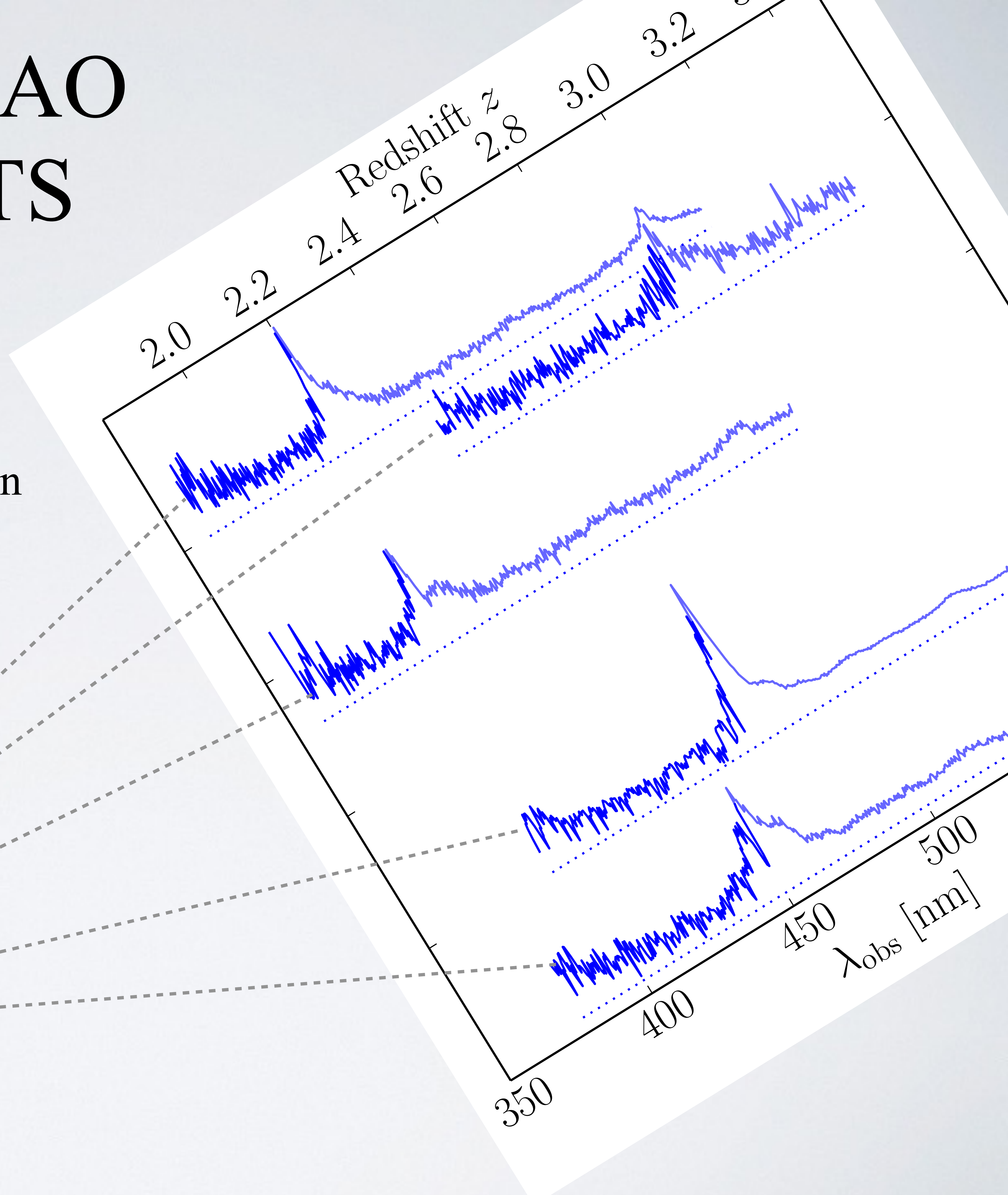
- Quasar redshifts: visual inspection

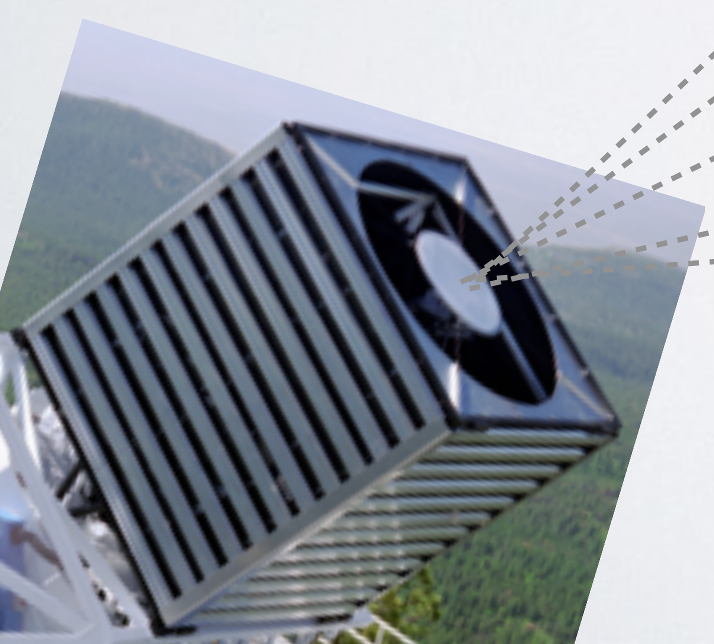




MEASURING BAO WITH FORESTS

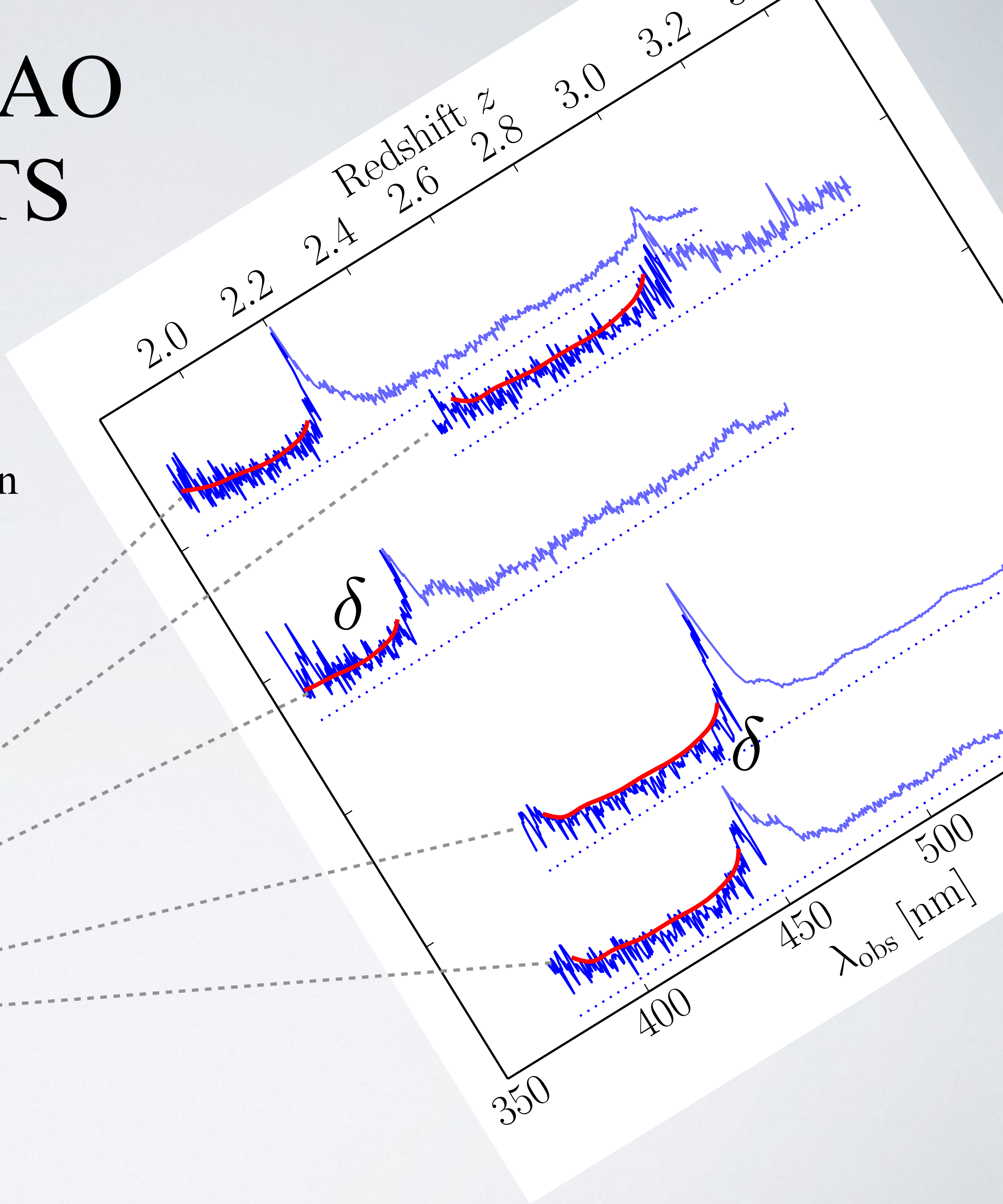
- Quasar redshifts: visual inspection
- Compute flux fluctuations





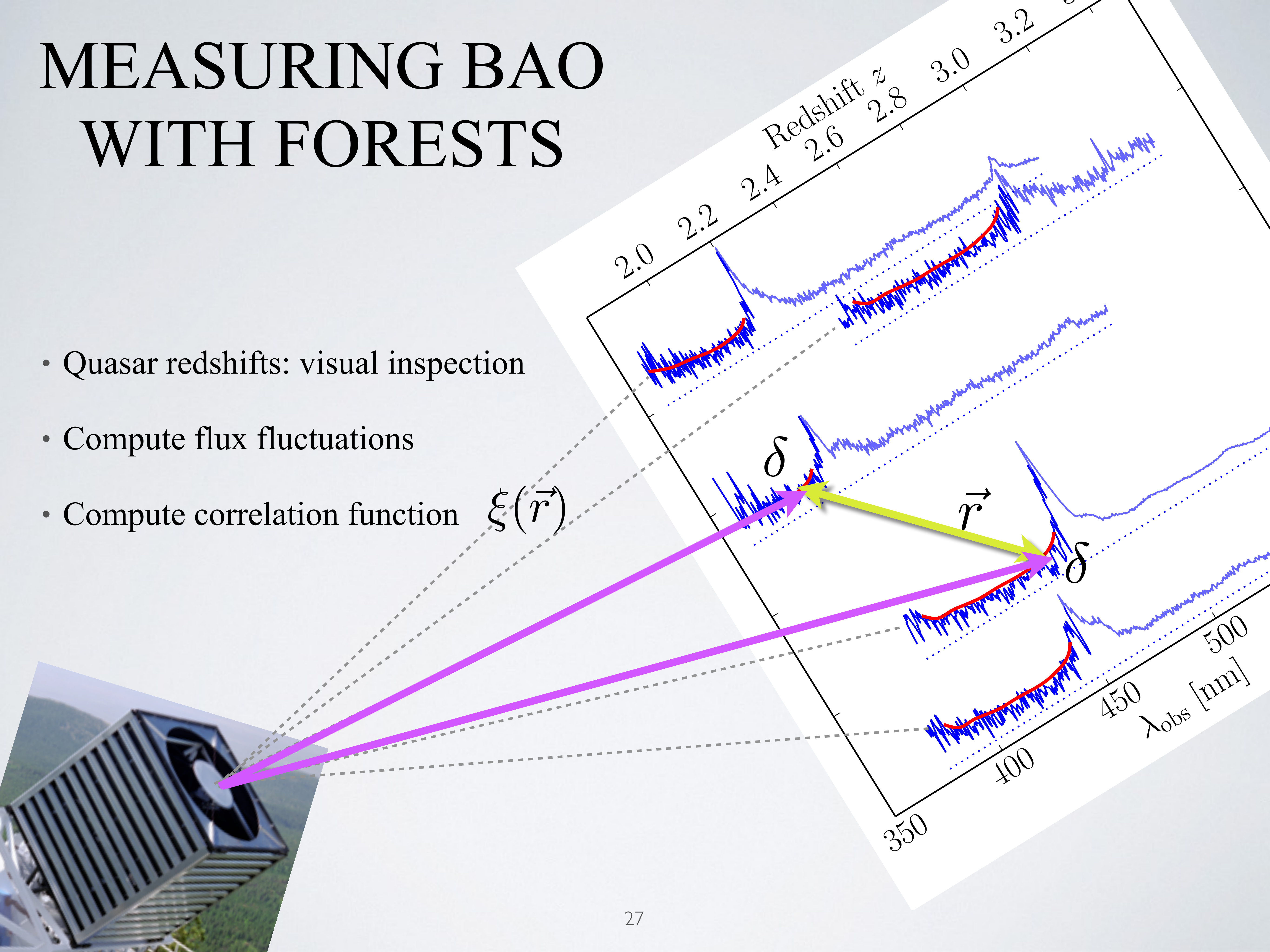
MEASURING BAO WITH FORESTS

- Quasar redshifts: visual inspection
- Compute flux fluctuations



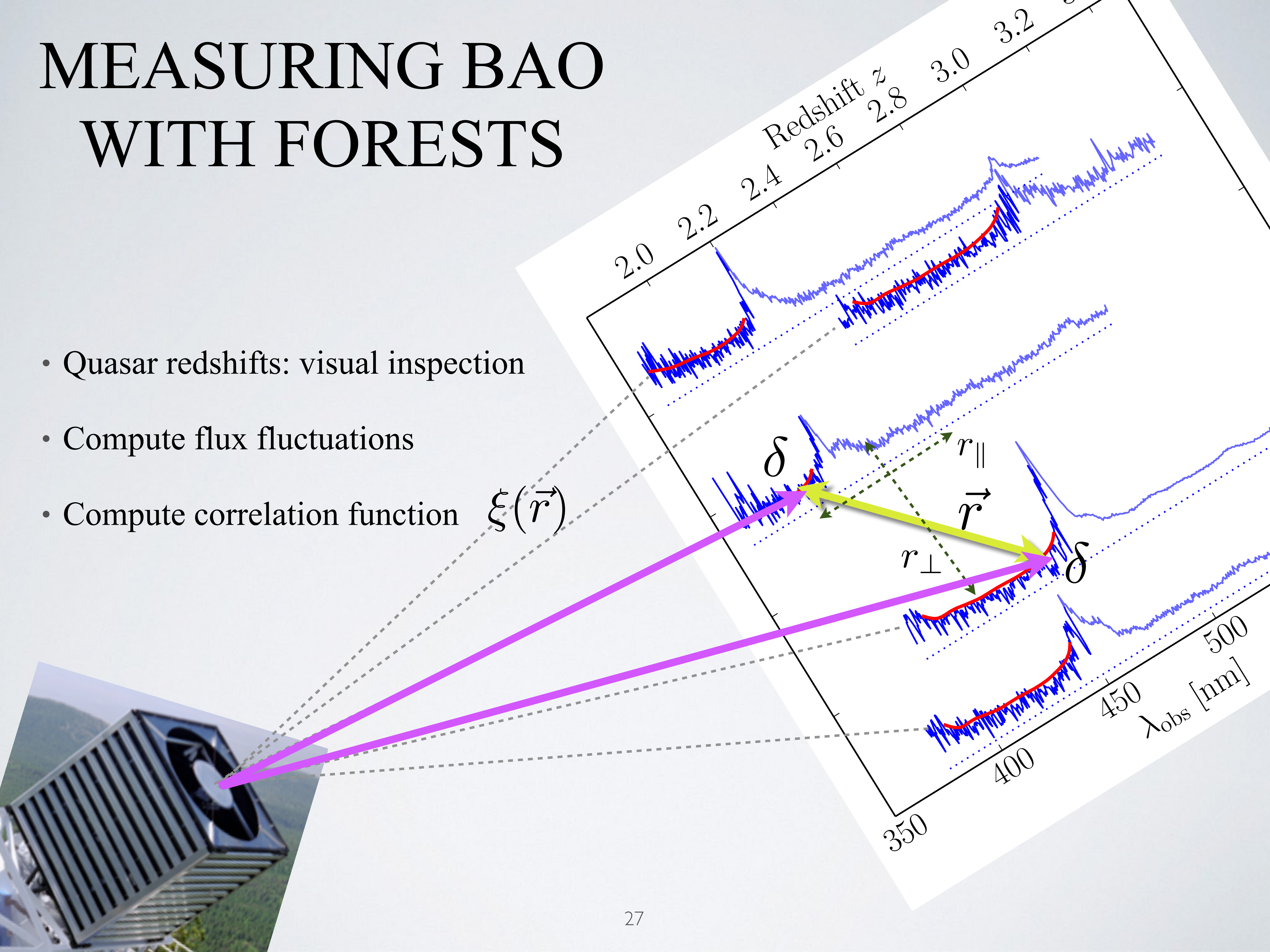
MEASURING BAO WITH FORESTS

- Quasar redshifts: visual inspection
- Compute flux fluctuations
- Compute correlation function $\xi(\vec{r})$



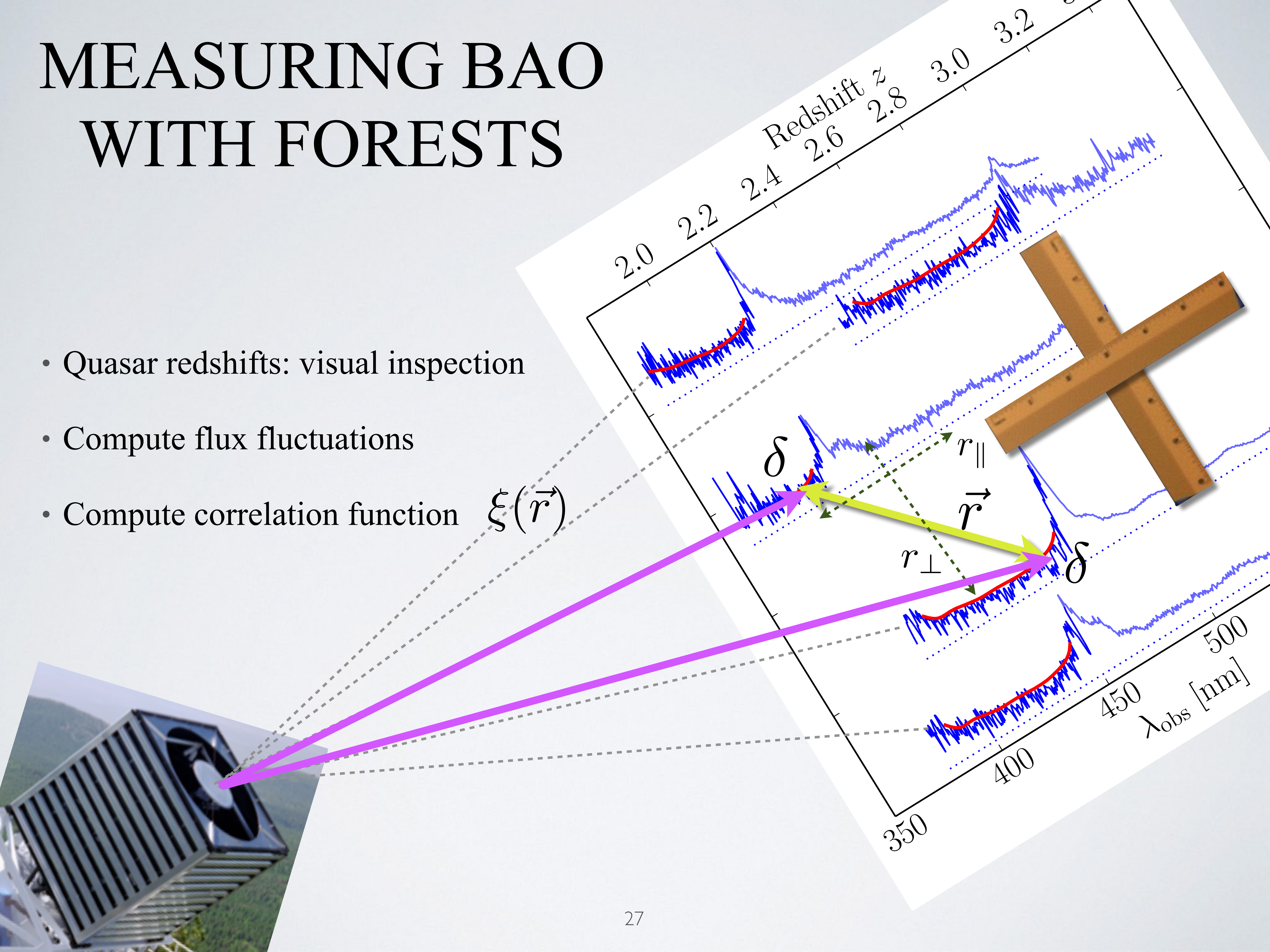
MEASURING BAO WITH FORESTS

- Quasar redshifts: visual inspection
- Compute flux fluctuations
- Compute correlation function $\xi(\vec{r})$



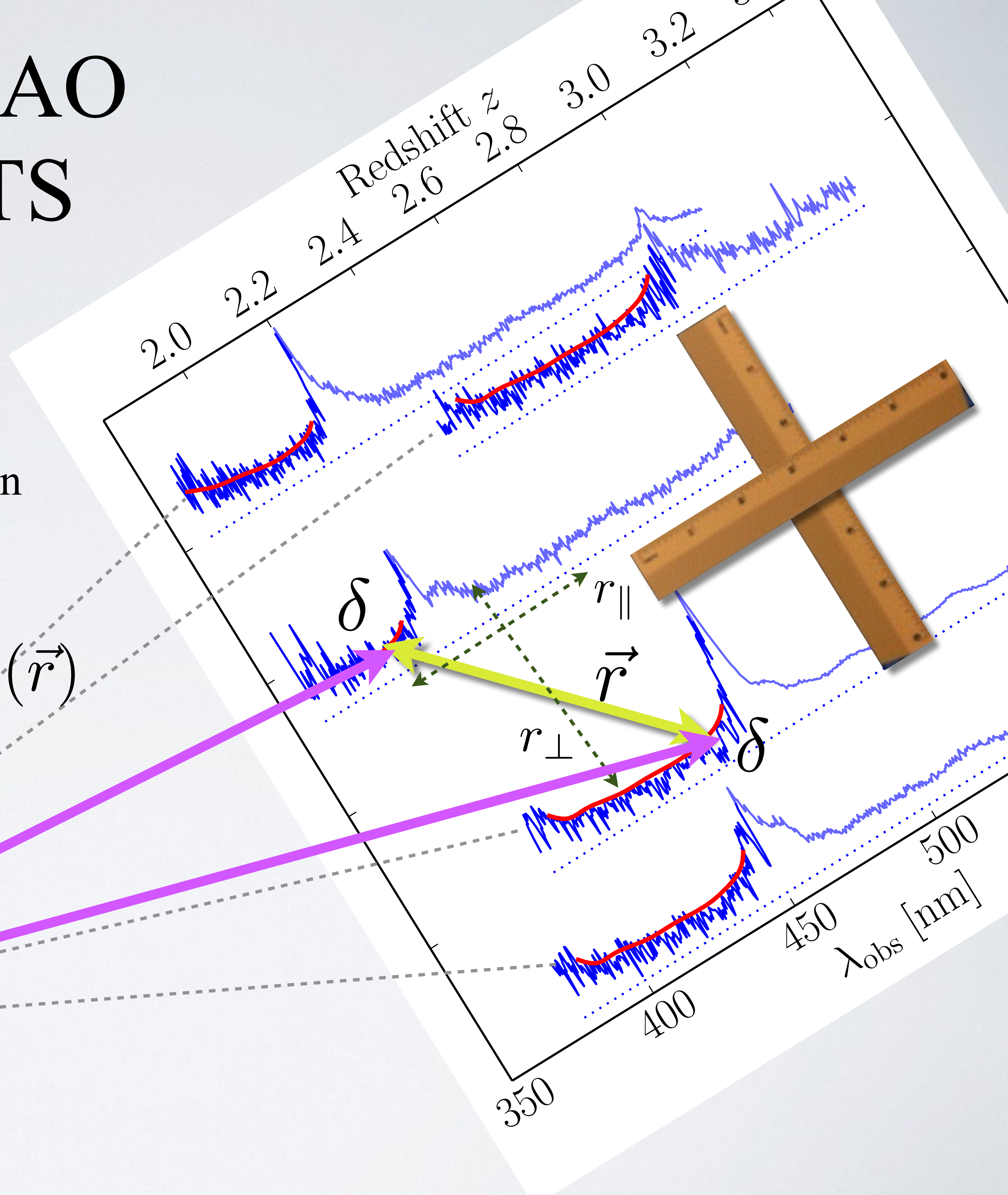
MEASURING BAO WITH FORESTS

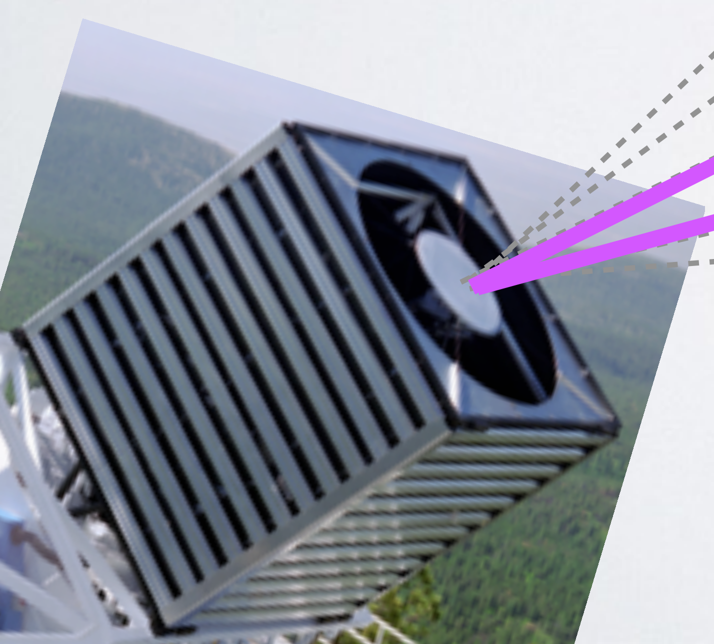
- Quasar redshifts: visual inspection
- Compute flux fluctuations
- Compute correlation function $\xi(\vec{r})$



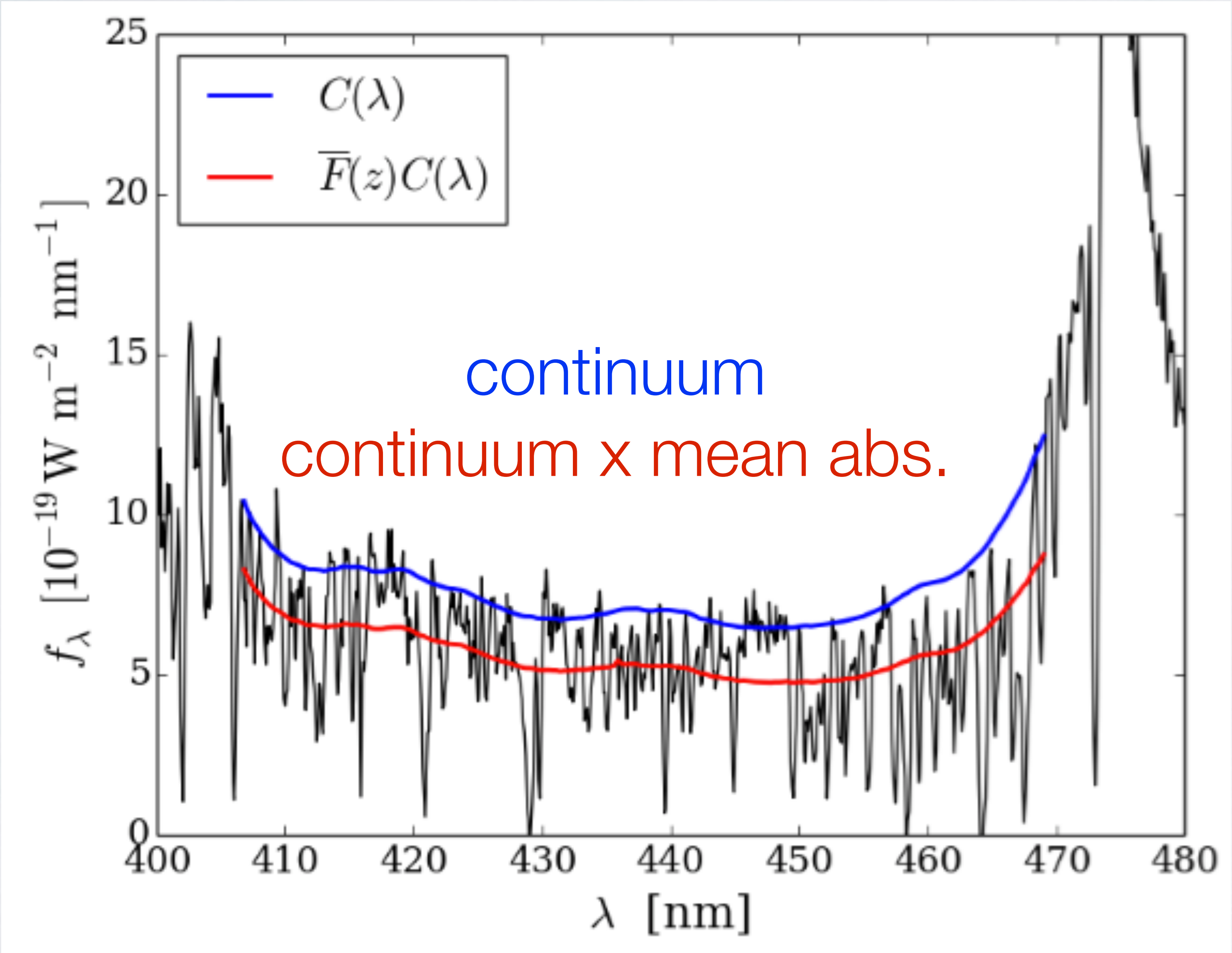
MEASURING BAO WITH FORESTS

- Quasar redshifts: visual inspection
- Compute flux fluctuations
- Compute correlation function $\xi(\vec{r})$
- Measure BAO scale



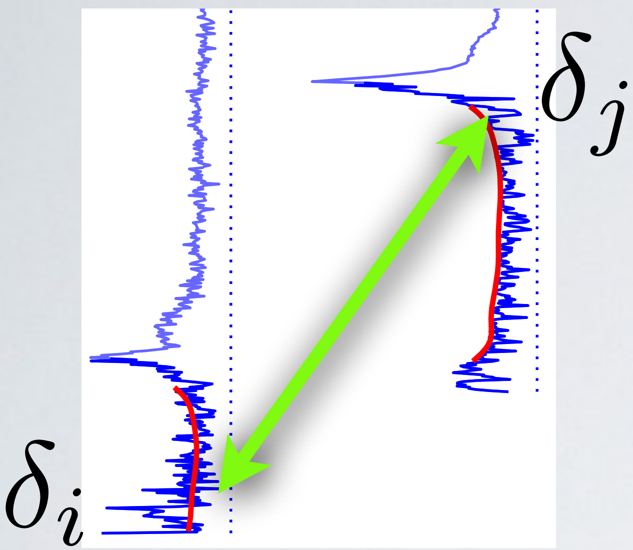


COMPUTING FLUCTUATIONS

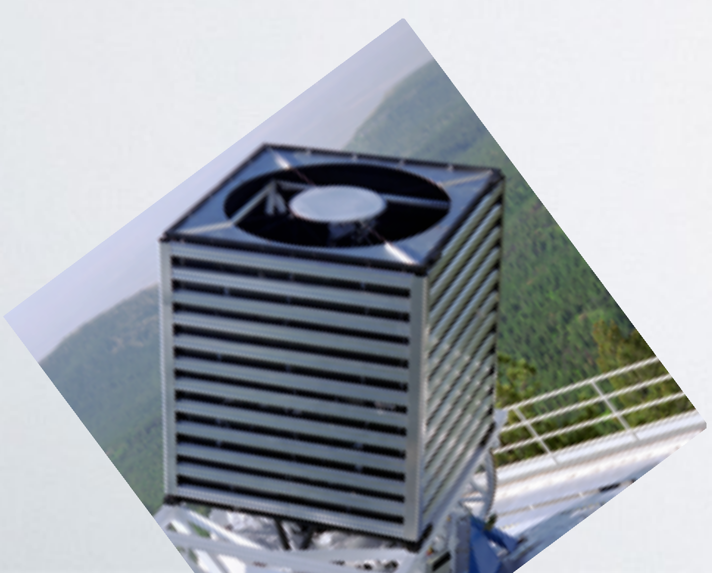


$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

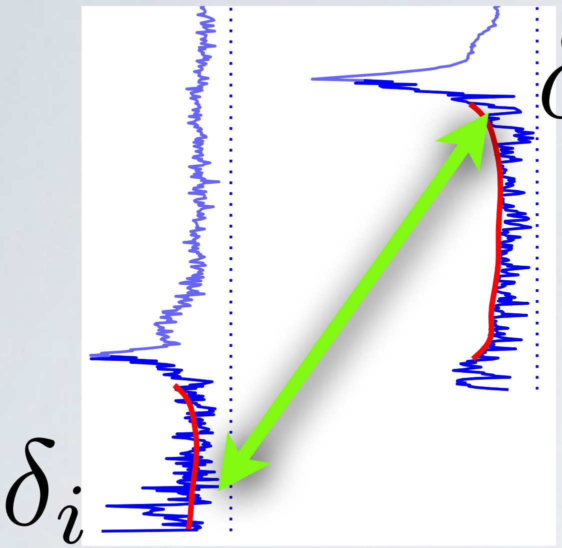
CORRELATION FUNCTION



$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

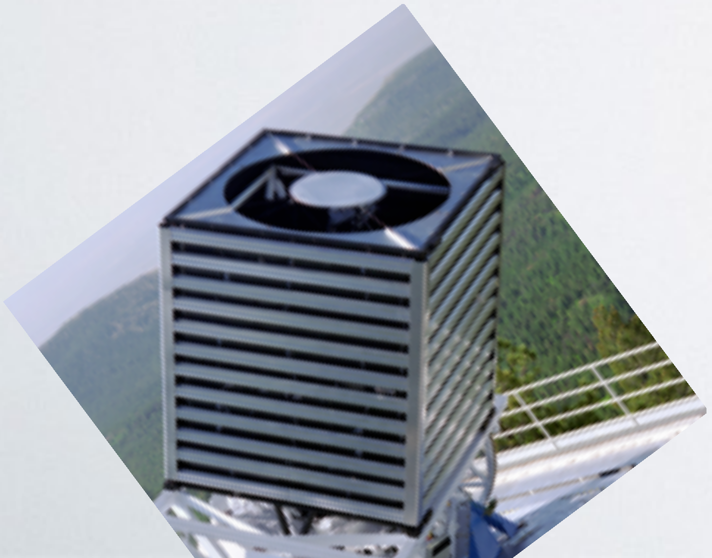


CORRELATION FUNCTION

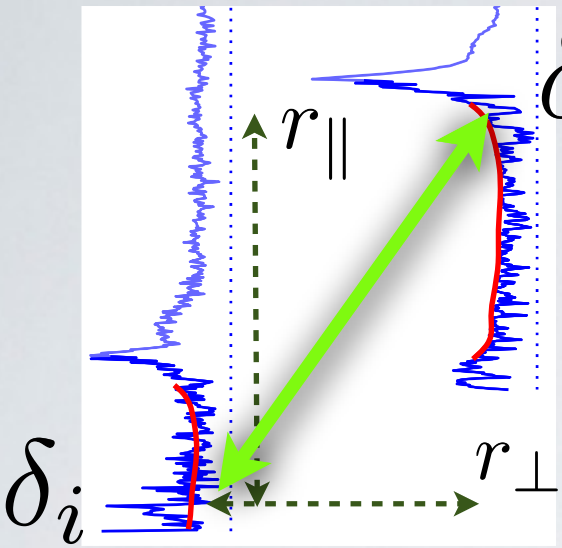


$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

$$\hat{\xi}(r_\perp, r_\parallel) = \langle \delta_i \delta_j \rangle$$

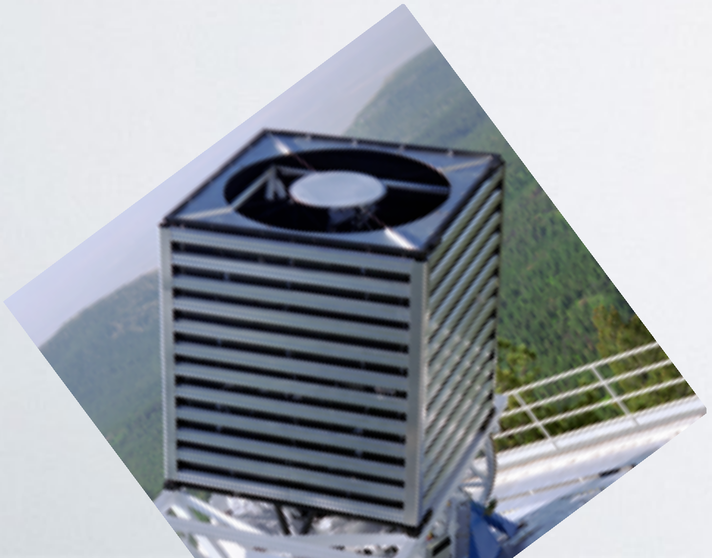


CORRELATION FUNCTION

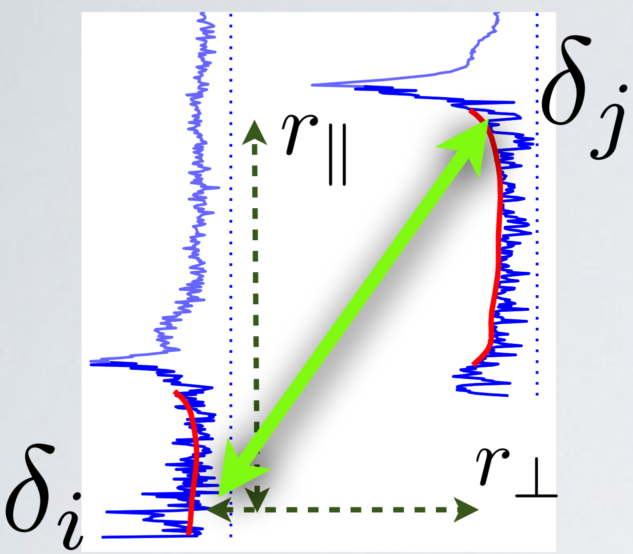


$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

$$\hat{\xi}(r_\perp, r_\parallel) = \langle \delta_i \delta_j \rangle$$

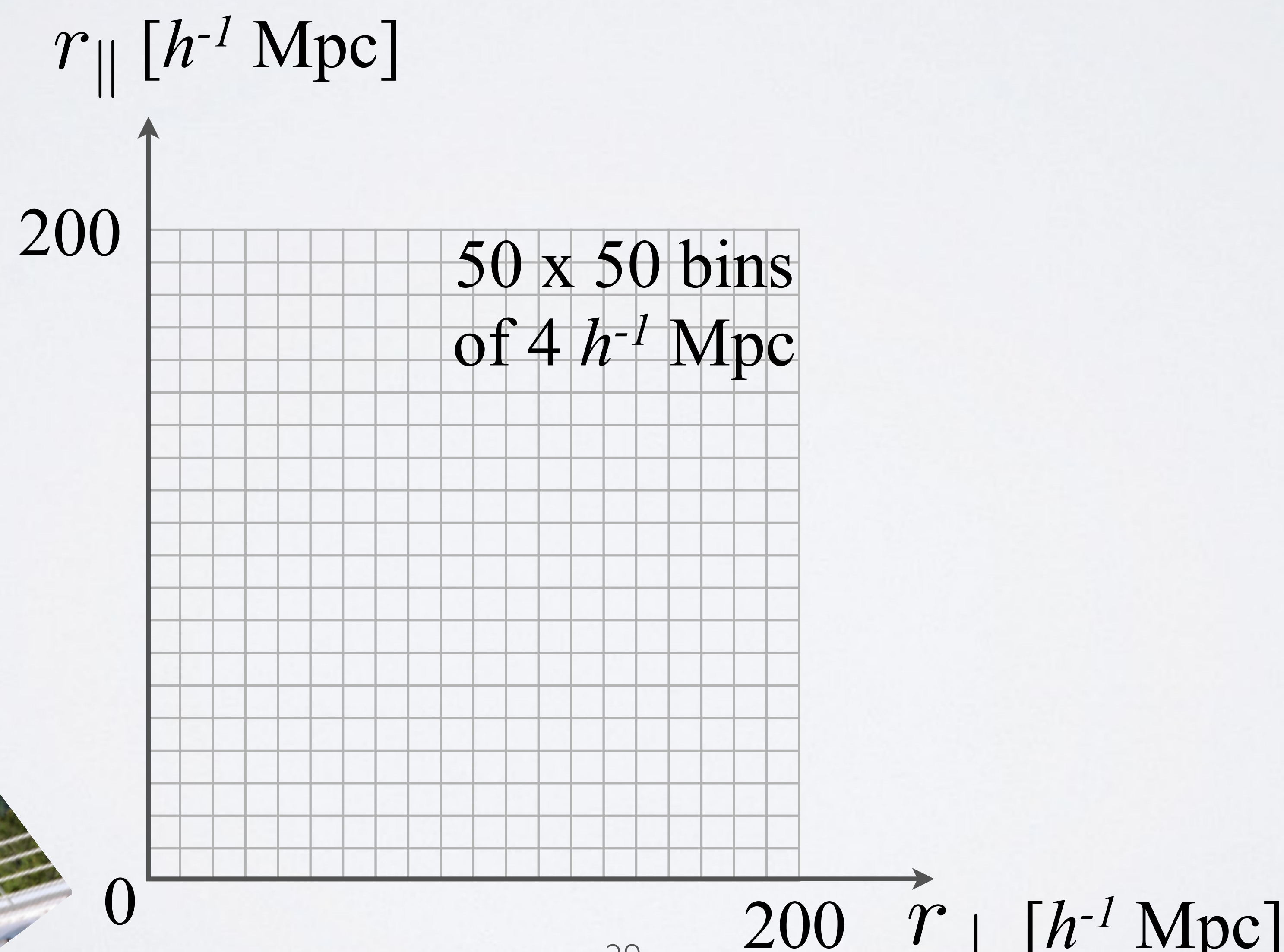


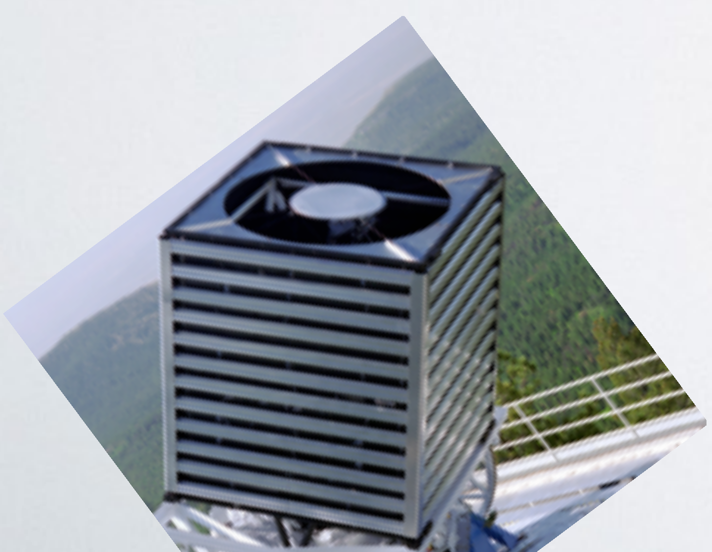
CORRELATION FUNCTION



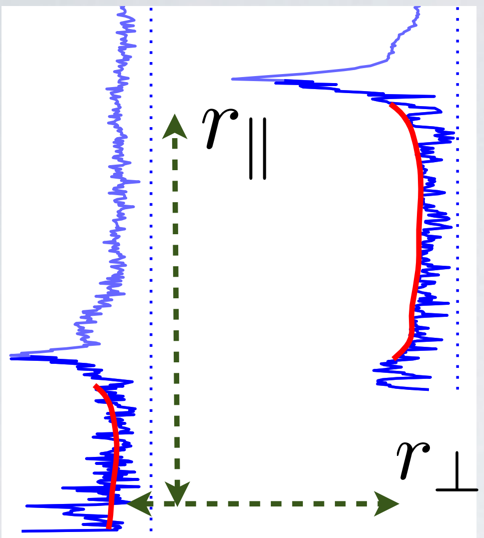
$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

$$\hat{\xi}(r_{\perp}, r_{\parallel}) = \langle \delta_i \delta_j \rangle$$



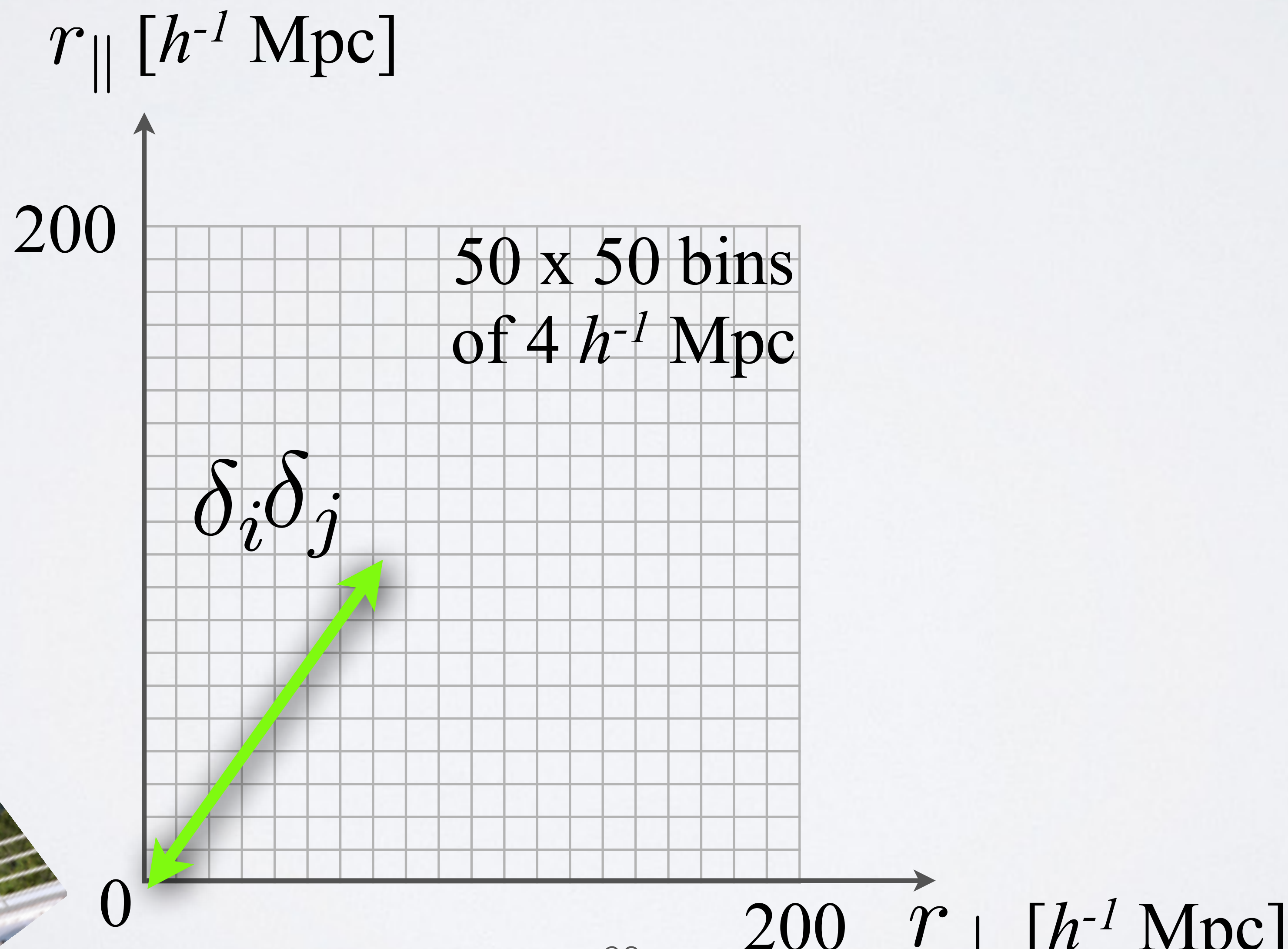


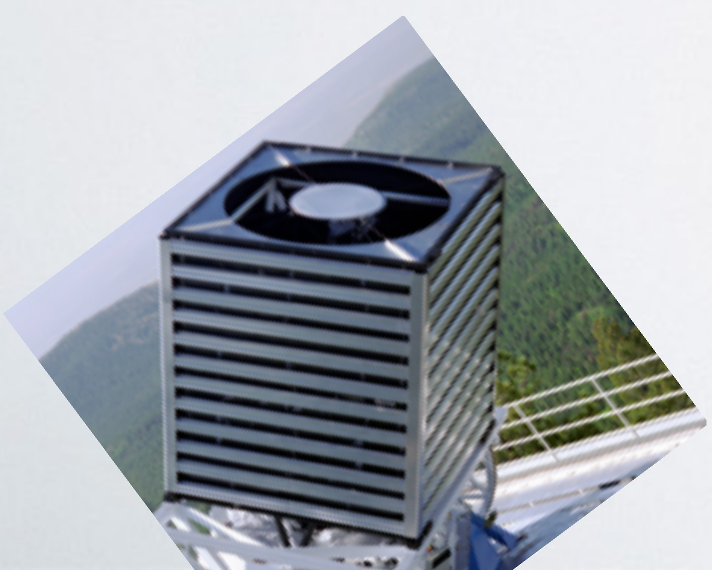
CORRELATION FUNCTION



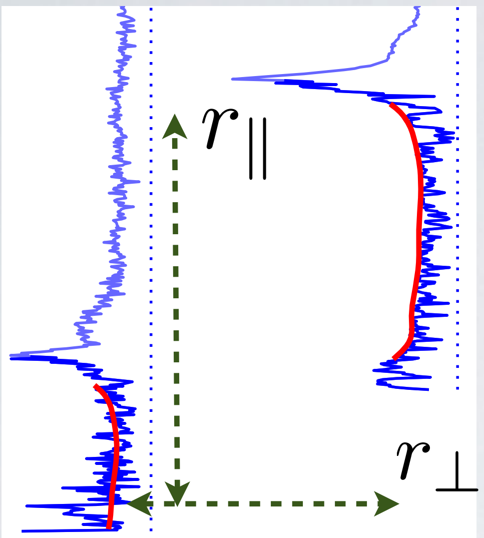
$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

$$\hat{\xi}(r_\perp, r_\parallel) = \langle \delta_i \delta_j \rangle$$



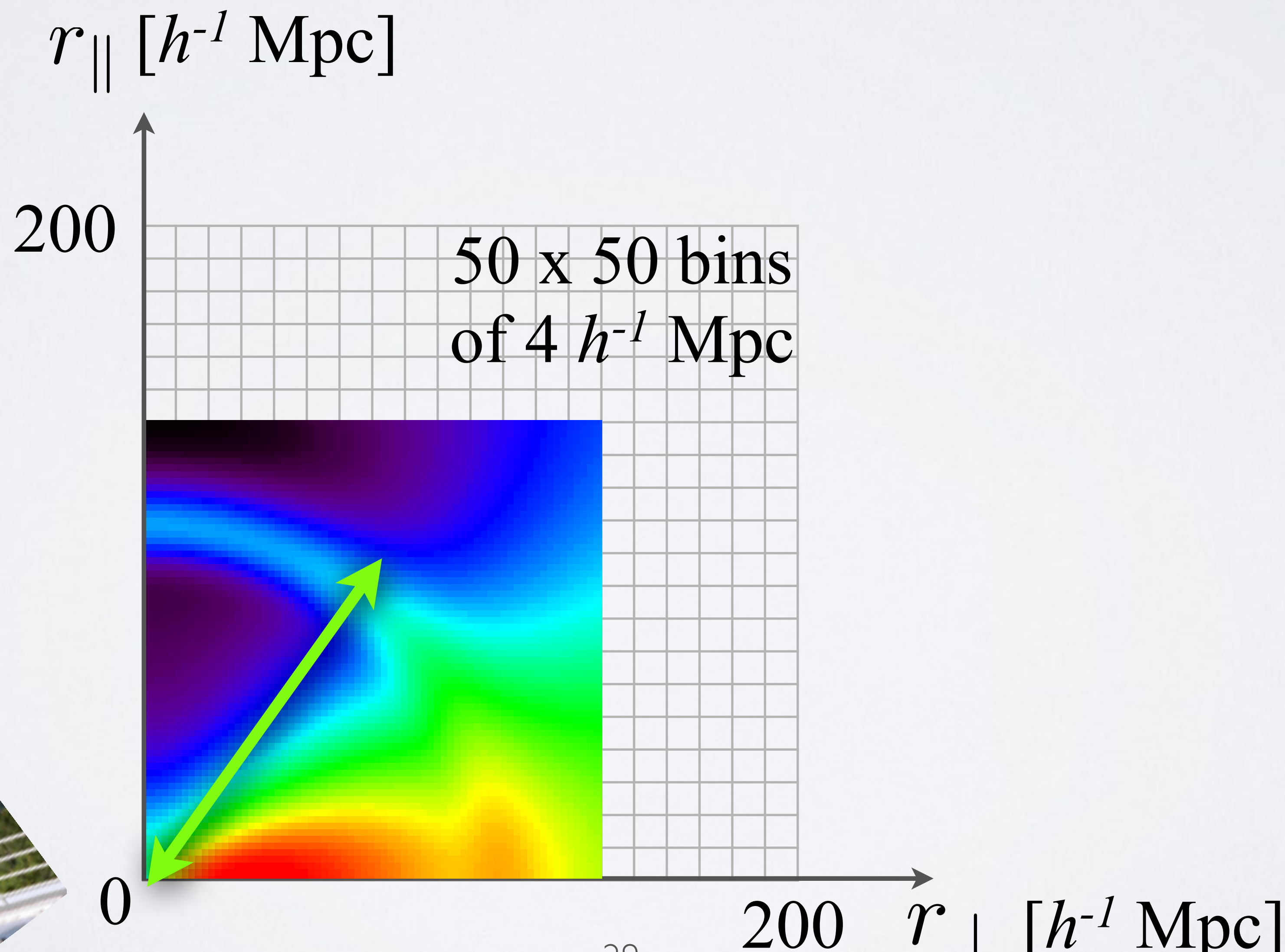


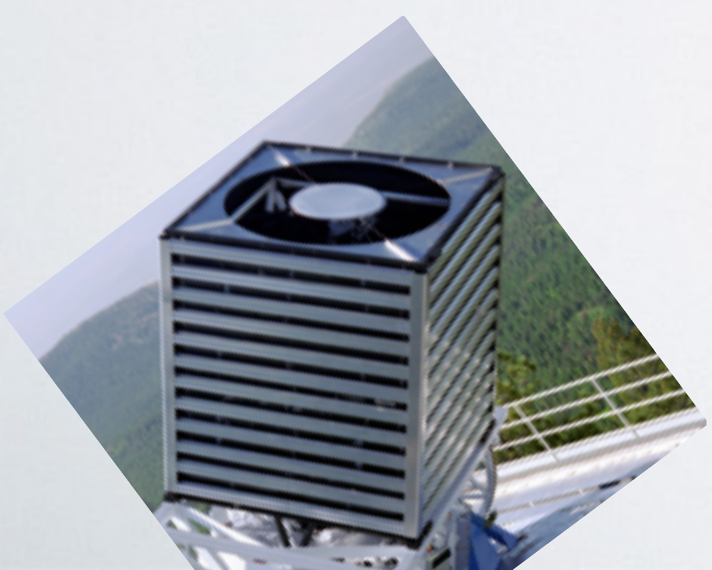
CORRELATION FUNCTION



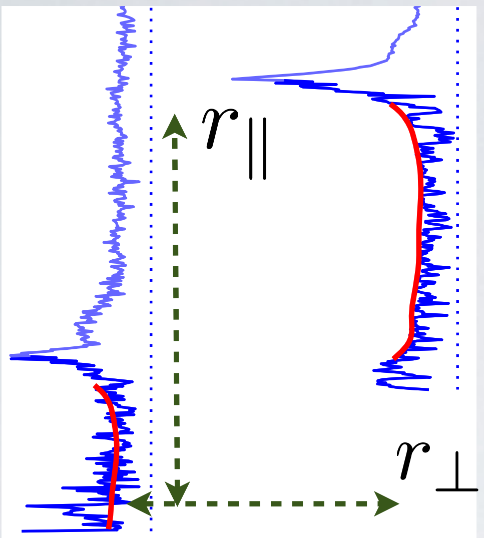
$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

$$\hat{\xi}(r_\perp, r_\parallel) = \langle \delta_i \delta_j \rangle$$



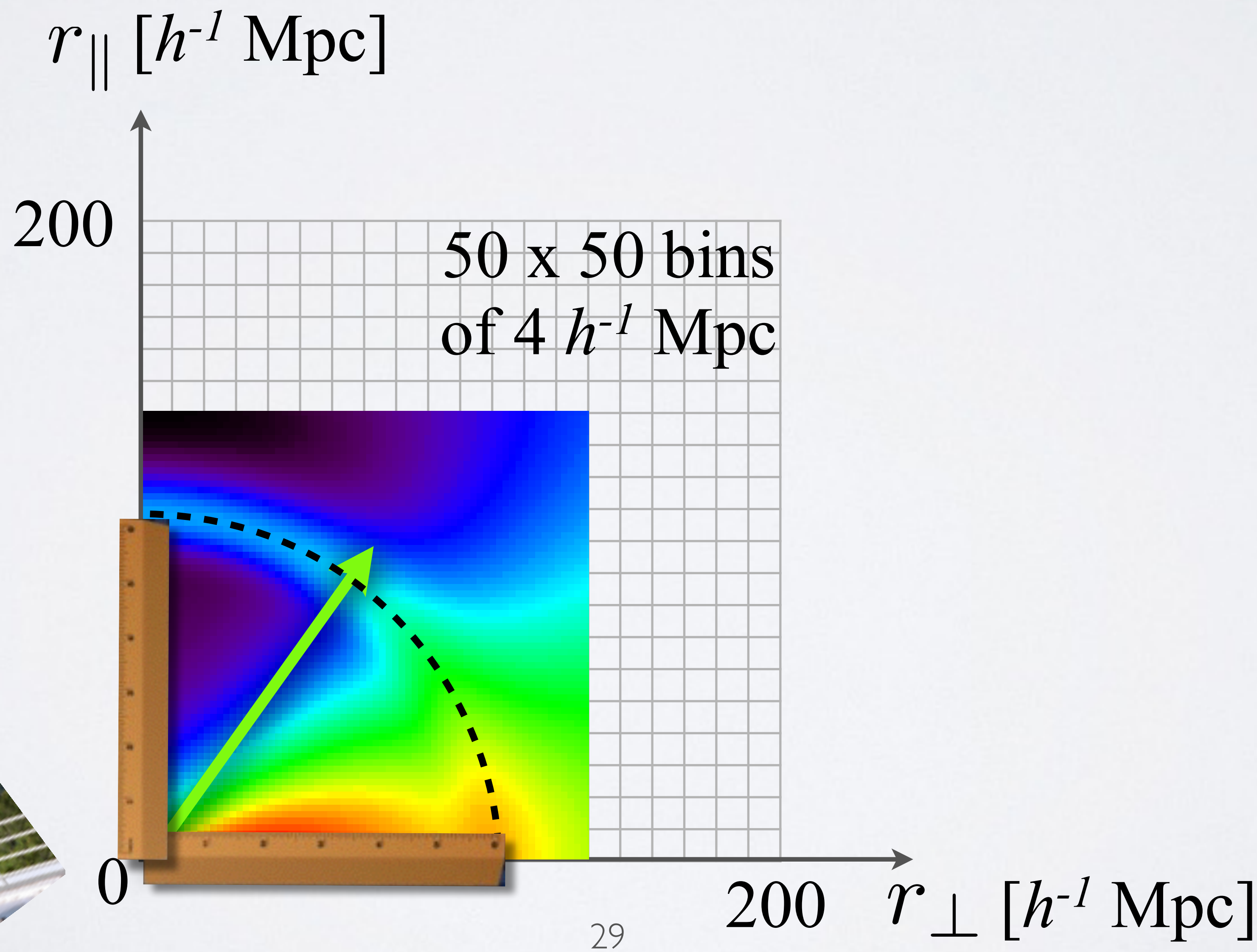


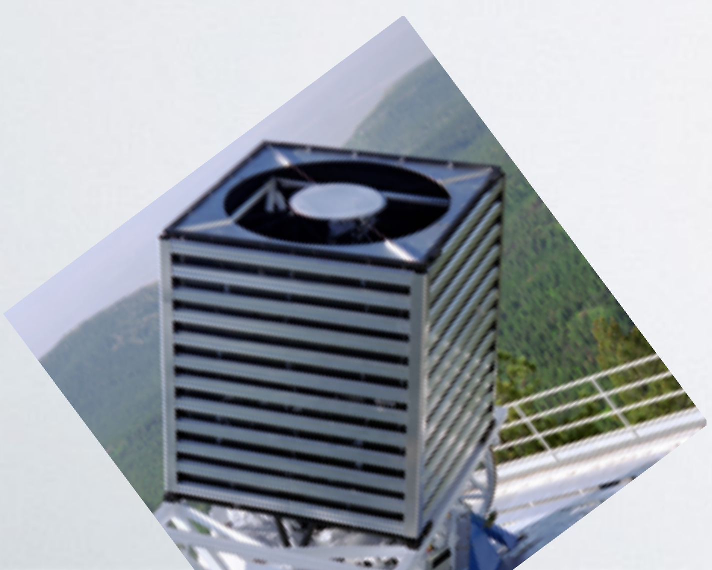
CORRELATION FUNCTION



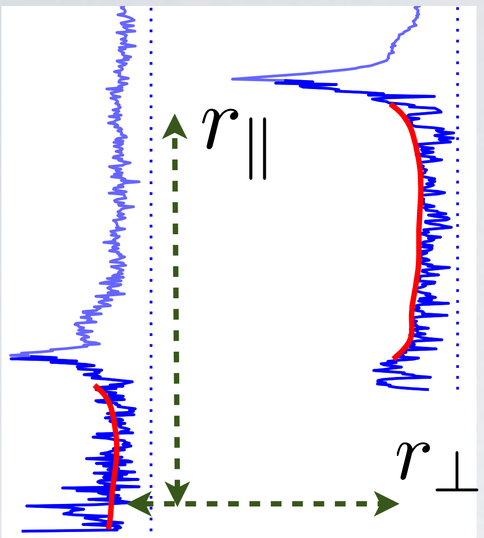
$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

$$\hat{\xi}(r_{\perp}, r_{\parallel}) = \langle \delta_i \delta_j \rangle$$



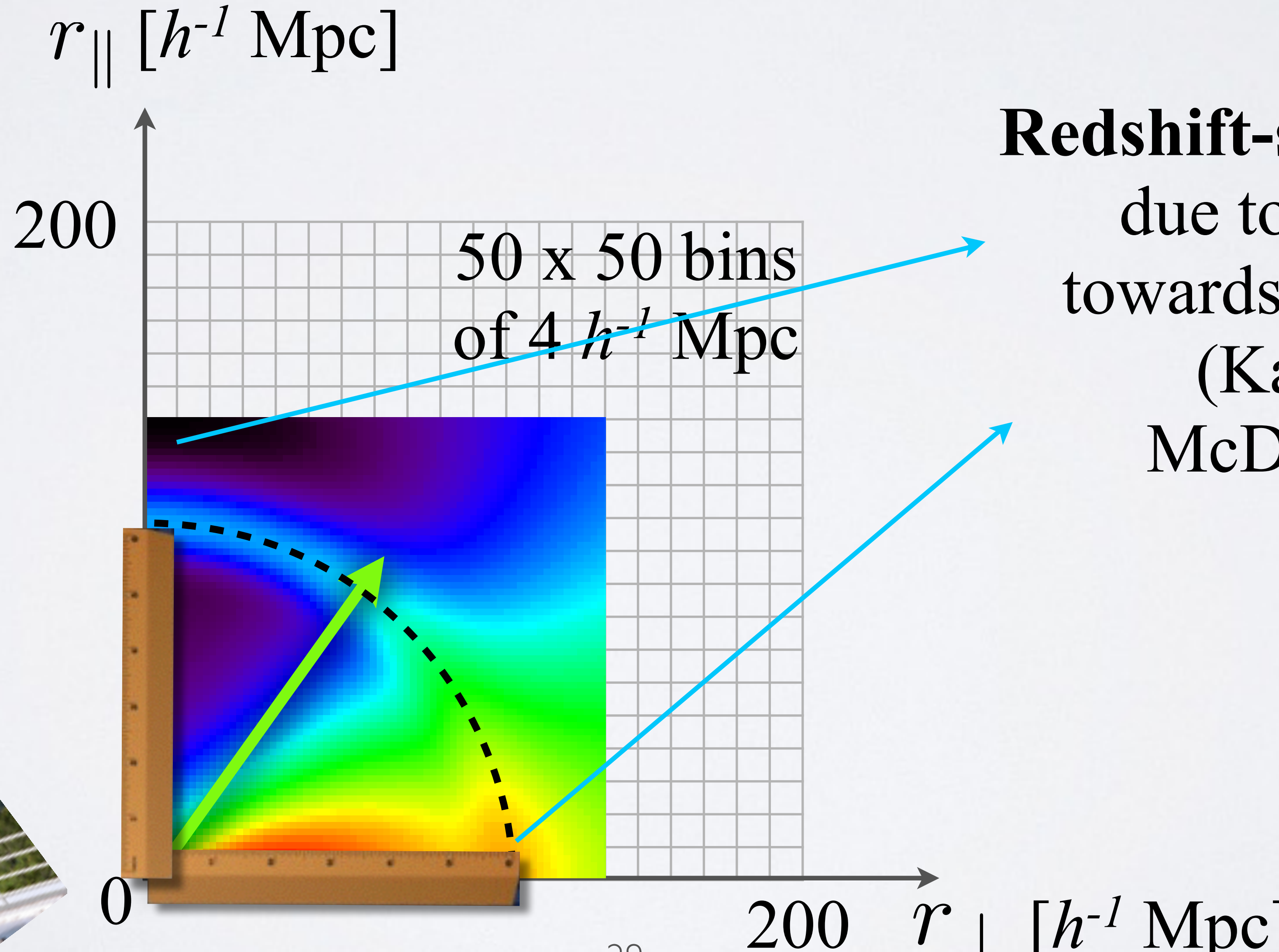


CORRELATION FUNCTION

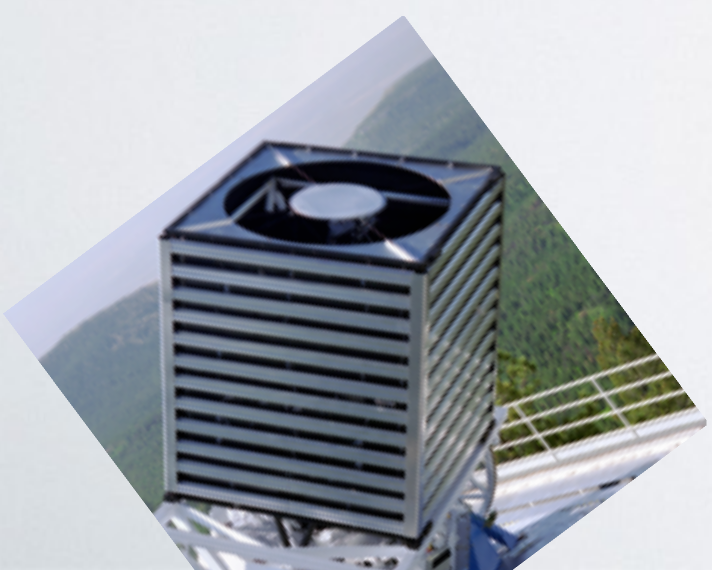


$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

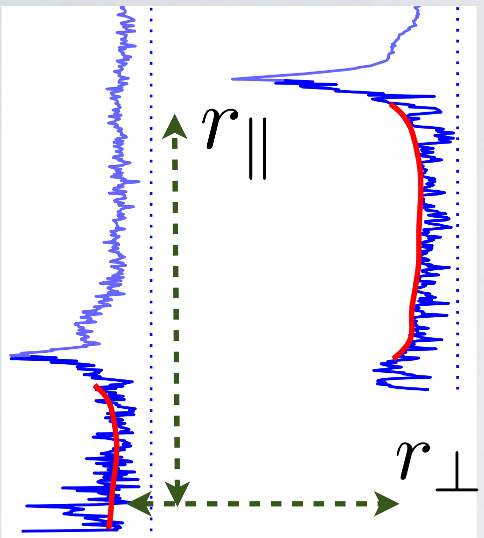
$$\hat{\xi}(r_\perp, r_\parallel) = \langle \delta_i \delta_j \rangle$$



Redshift-space distortions
due to matter infall
towards potential wells
(Kaiser 1987,
McDonald 2003)

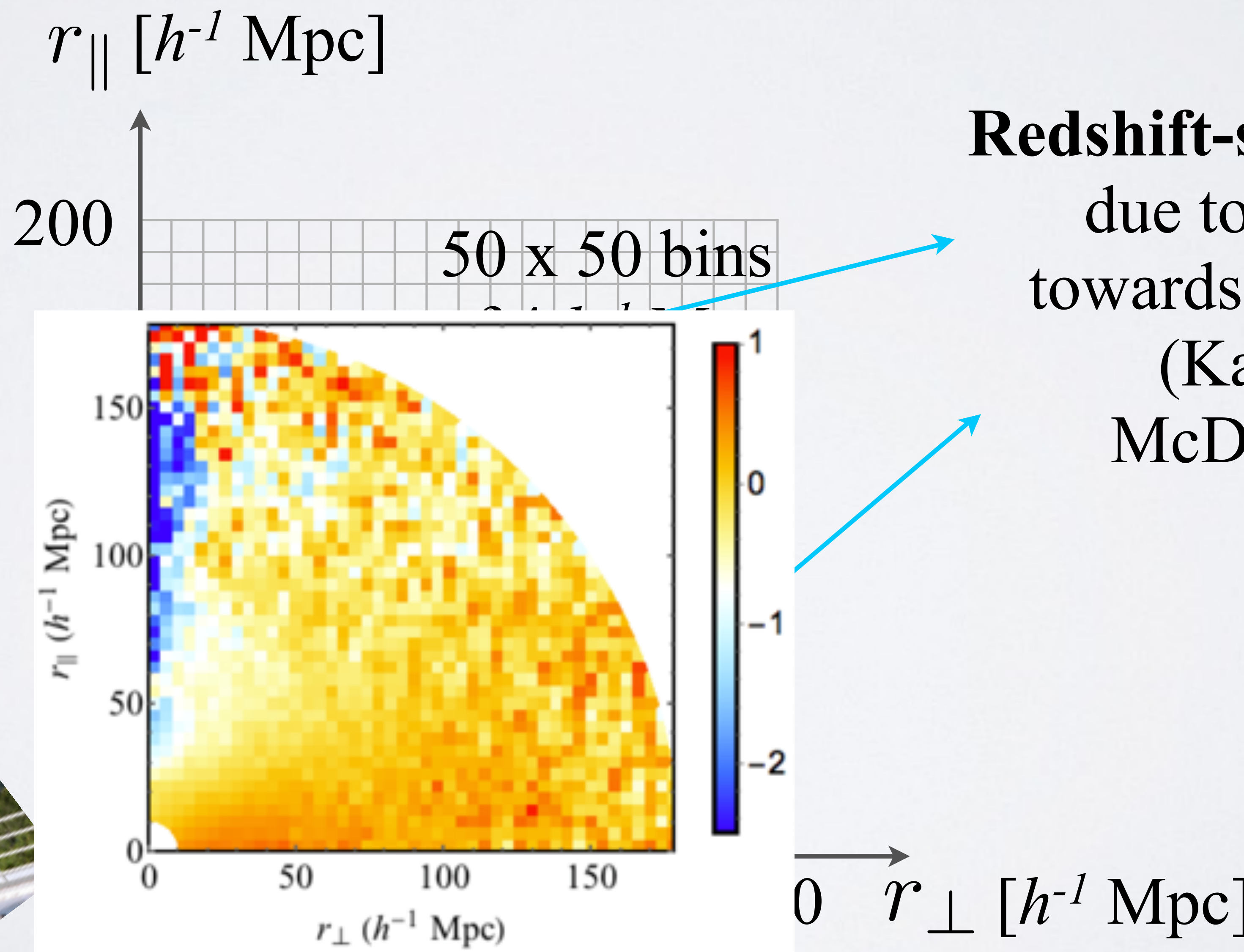


CORRELATION FUNCTION

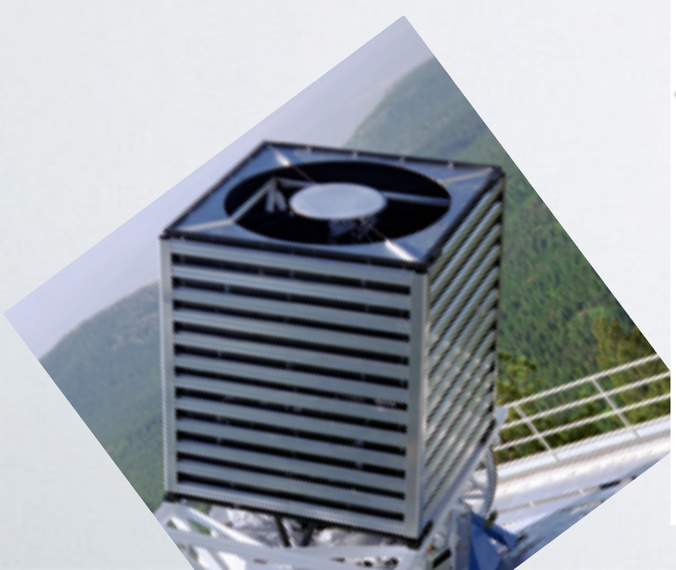


$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

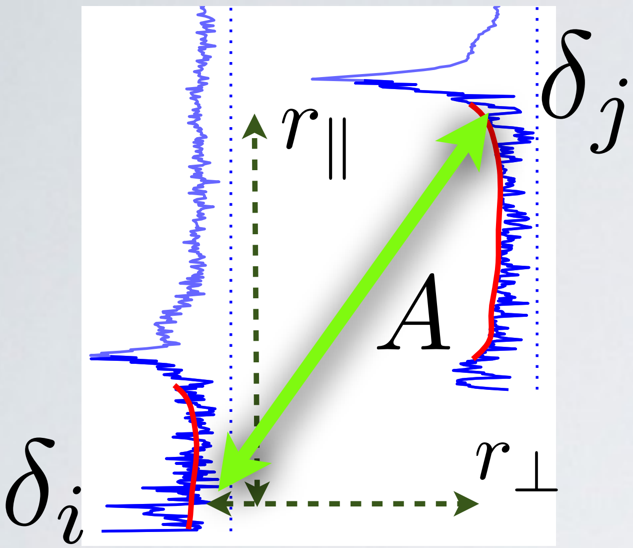
$$\hat{\xi}(r_{\perp}, r_{\parallel}) = \langle \delta_i \delta_j \rangle$$



Redshift-space distortions
due to matter infall
towards potential wells
(Kaiser 1987,
McDonald 2003)

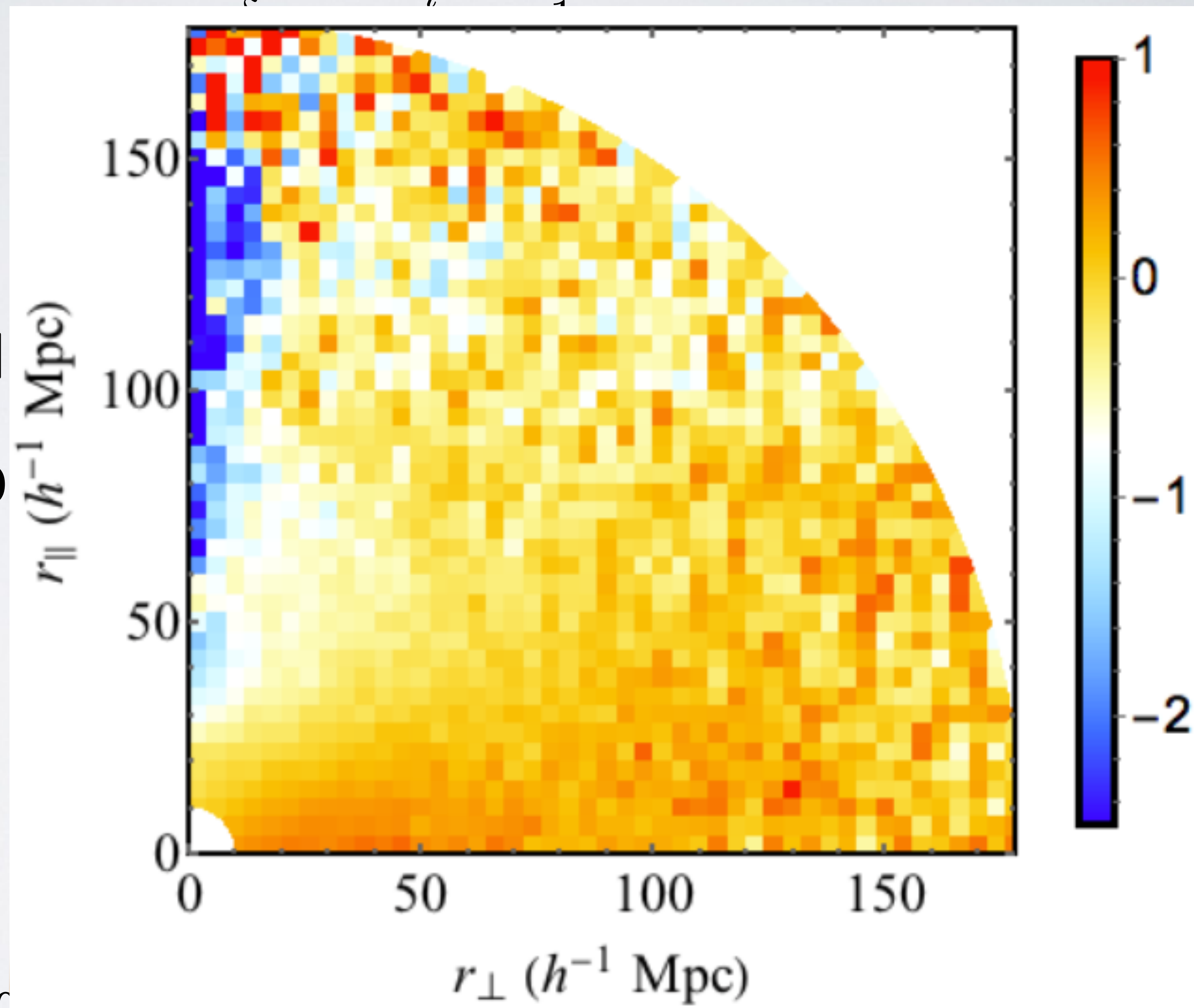


CORRELATION FUNCTION



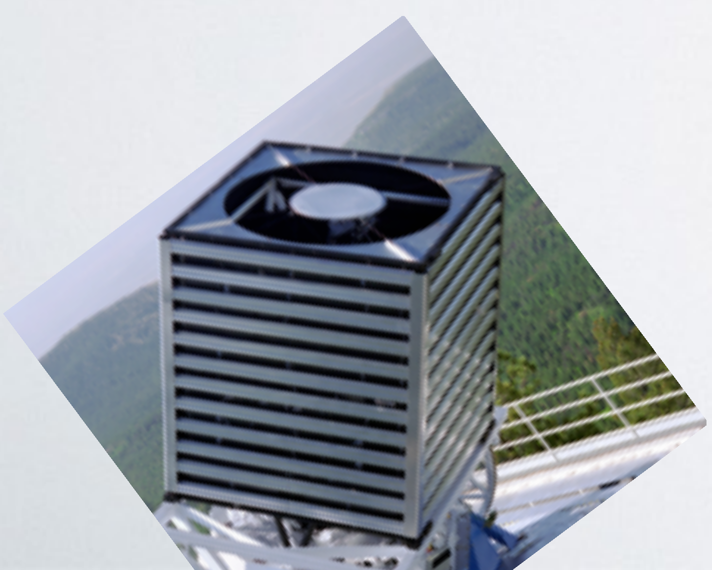
$r_\parallel$

200



ions

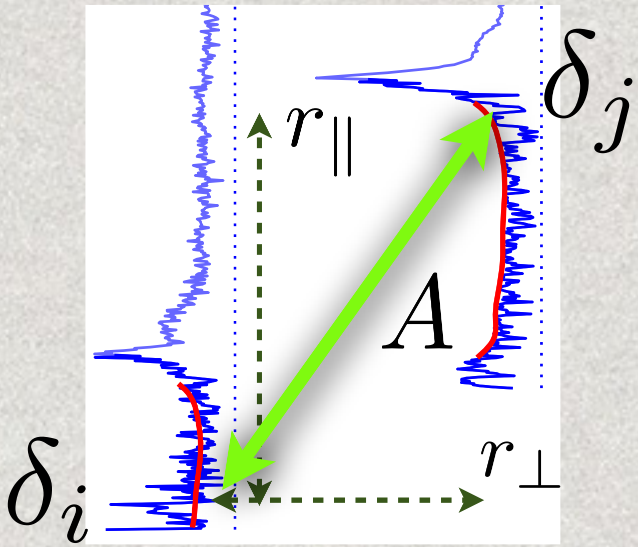
lls

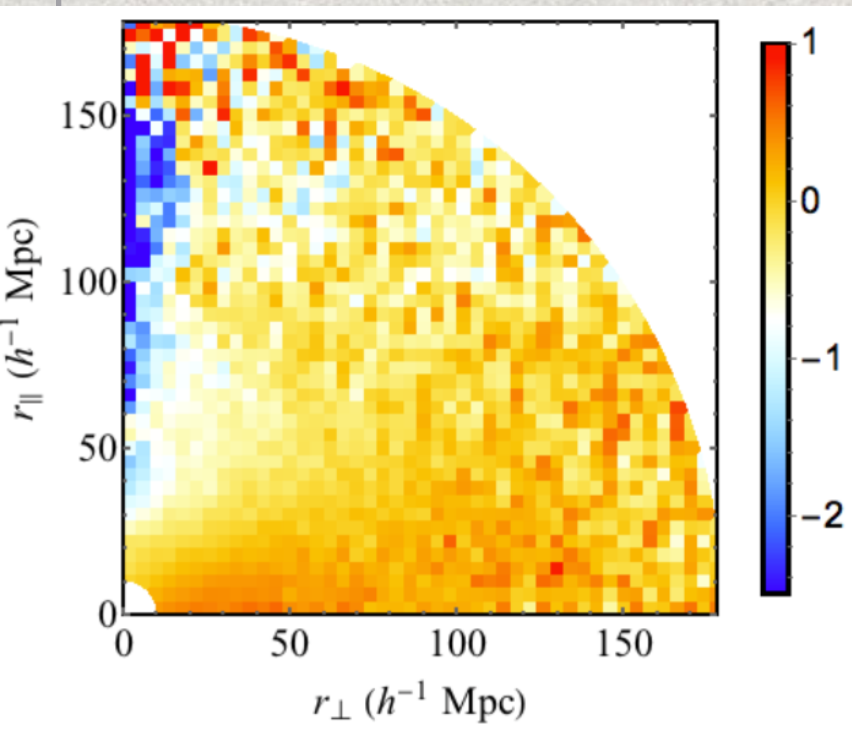


0

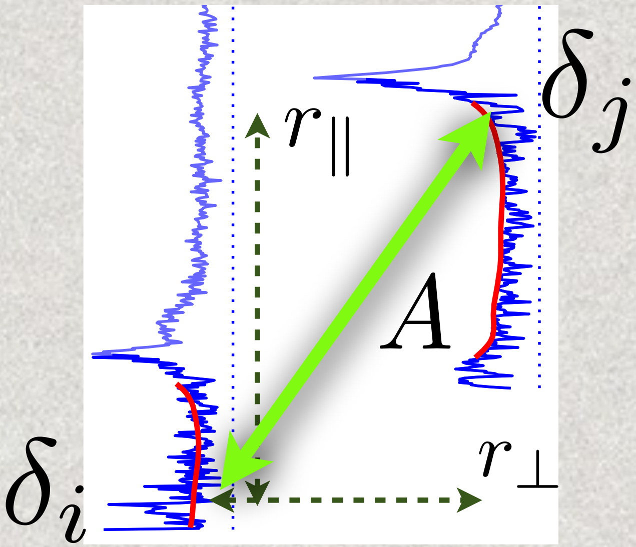
200 $r_\perp$ [h^{-1} Mpc]

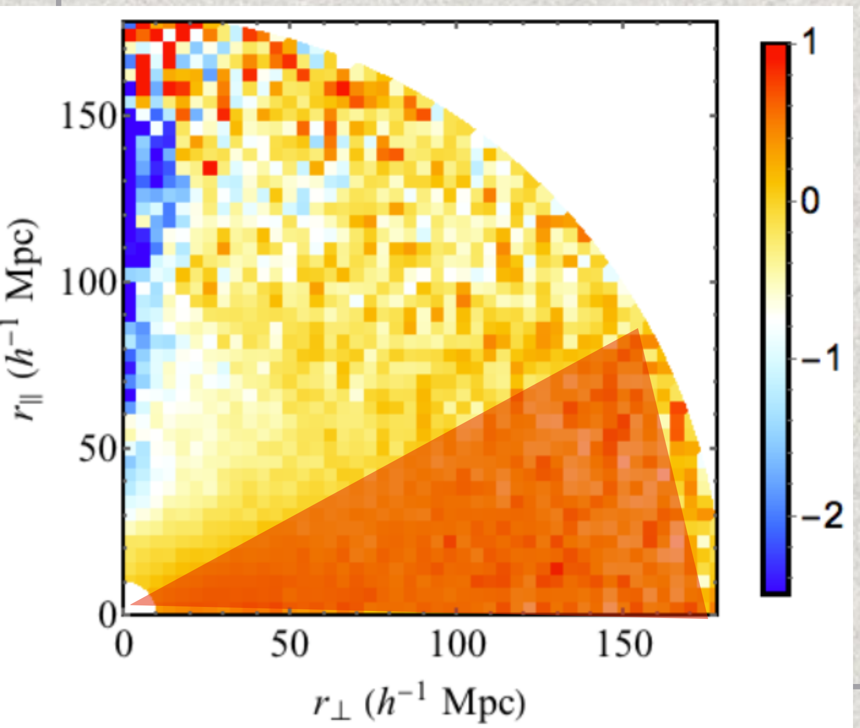
CORRELATION FUNCTION

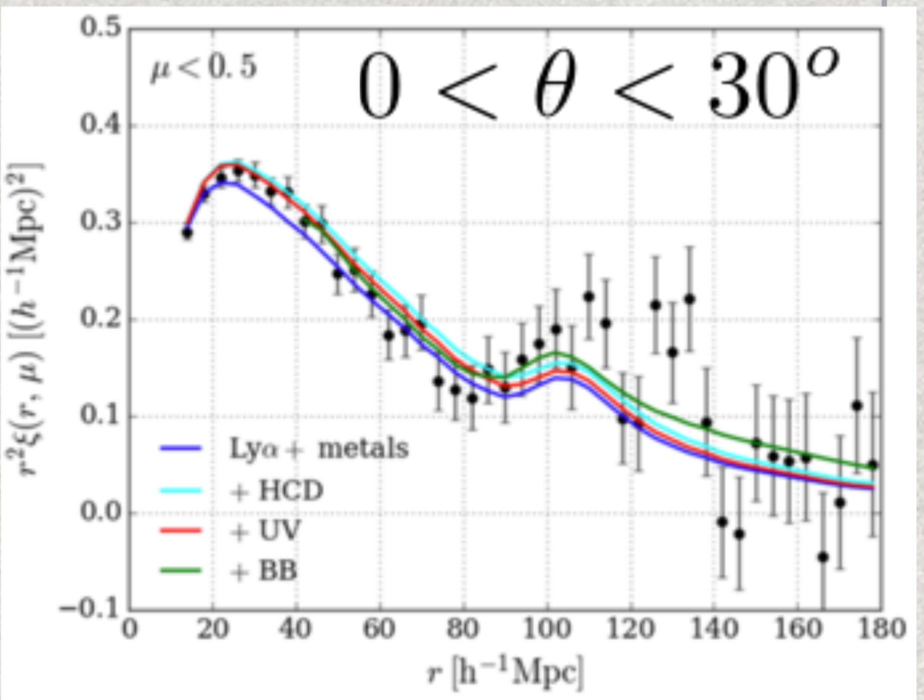




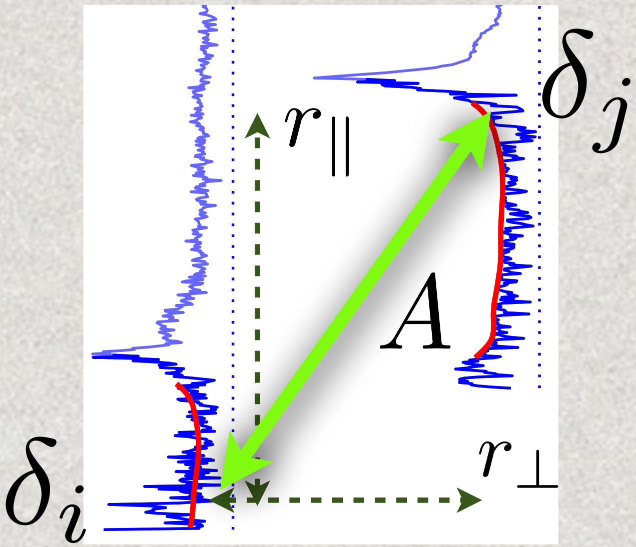
CORRELATION FUNCTION

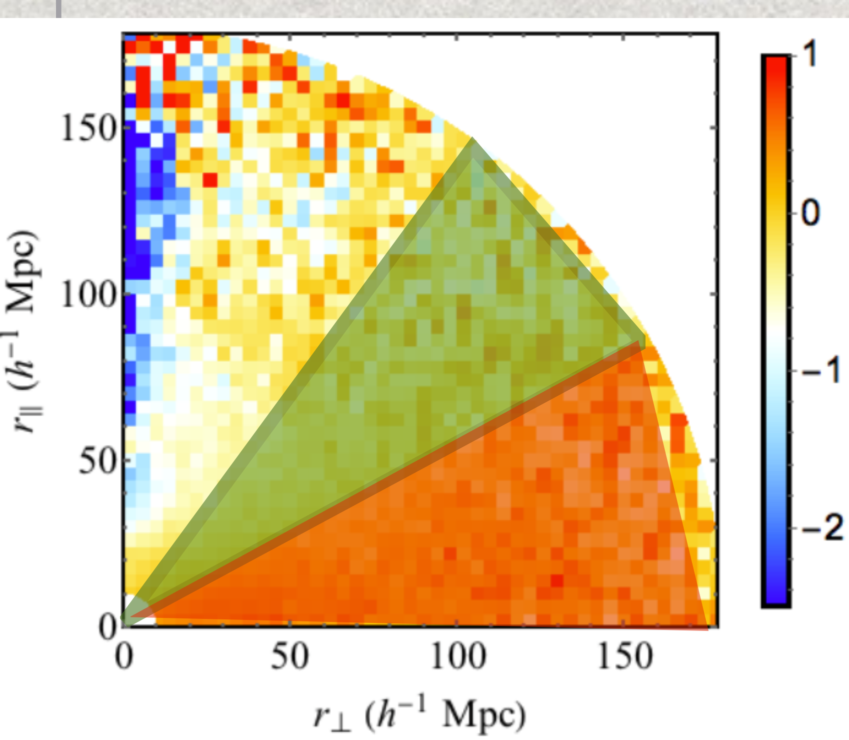


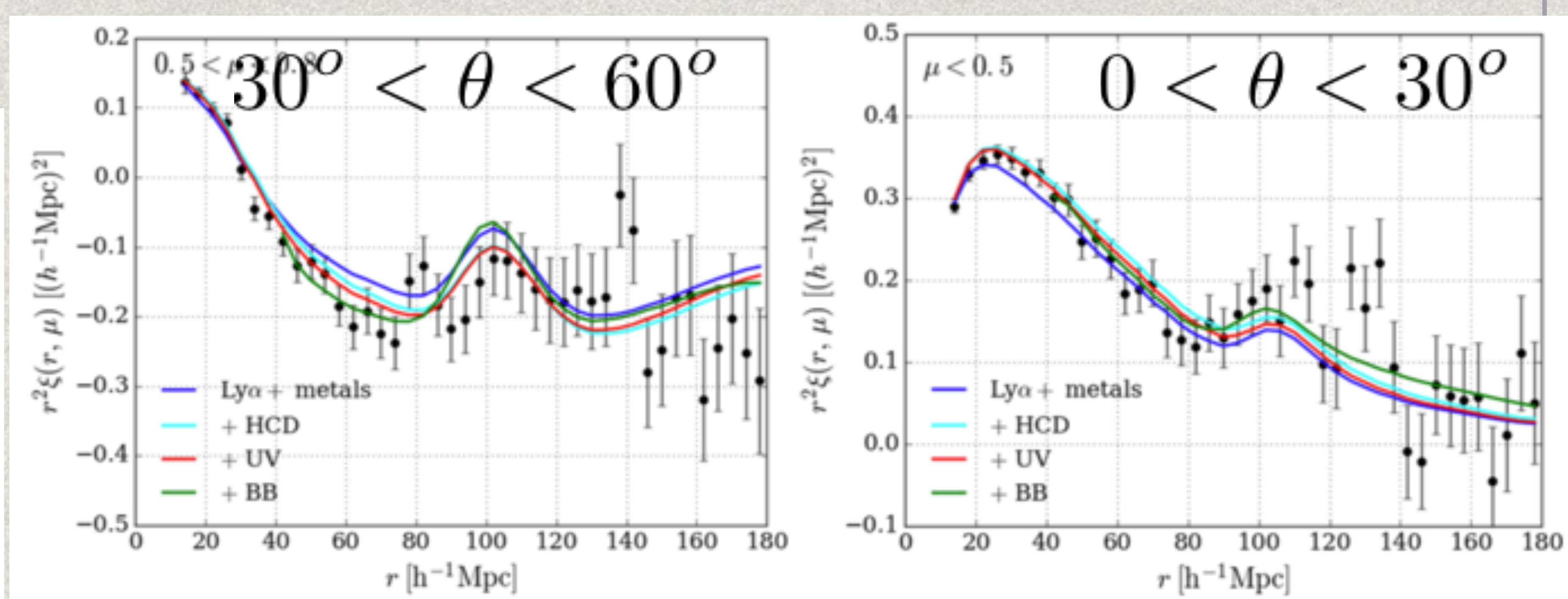




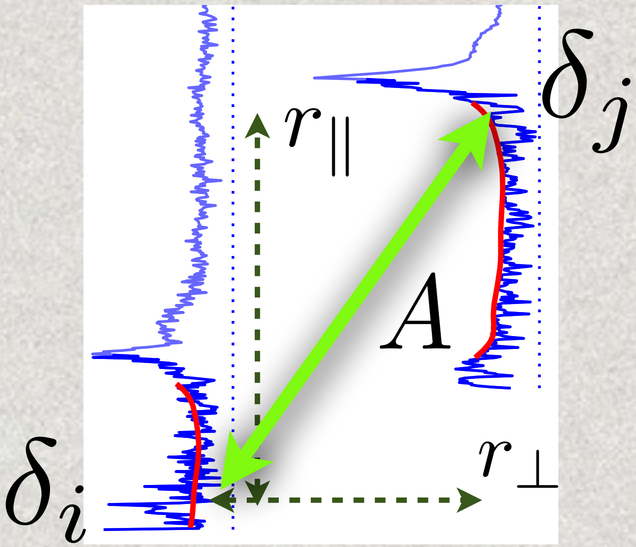
CORRELATION FUNCTION



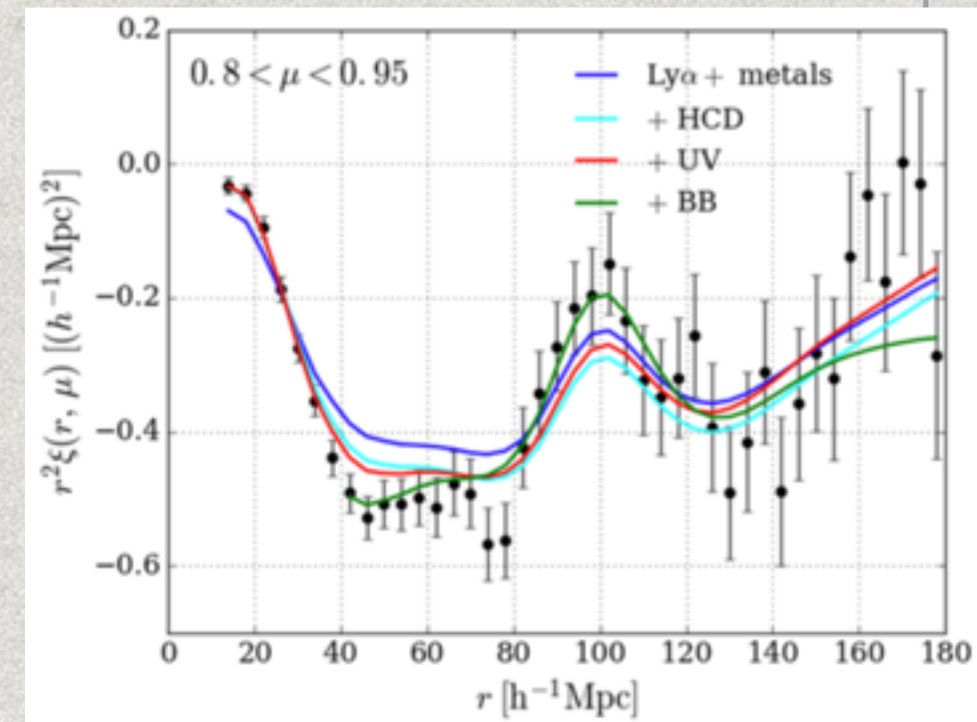


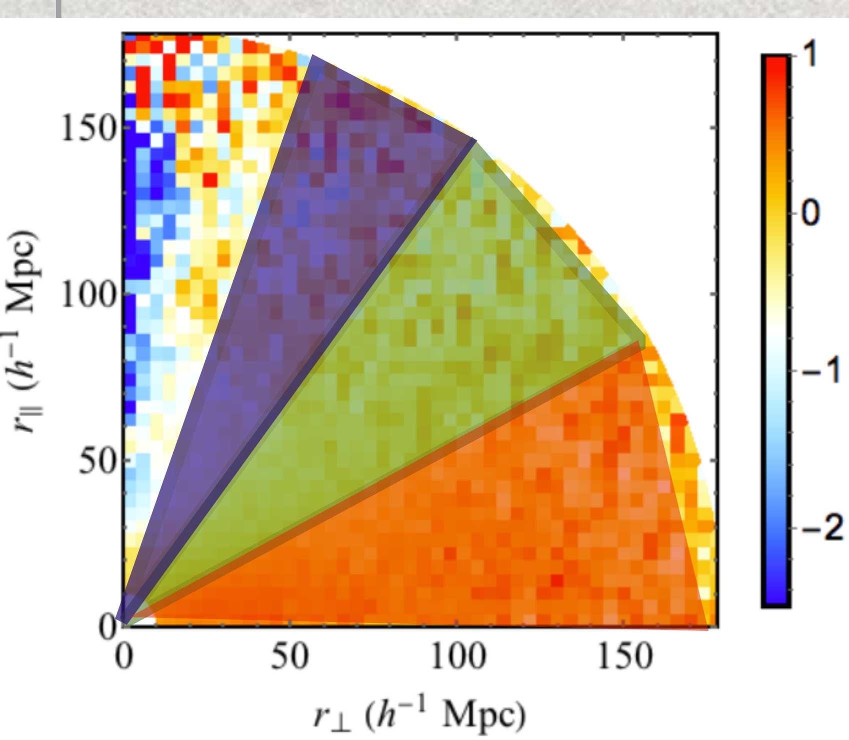


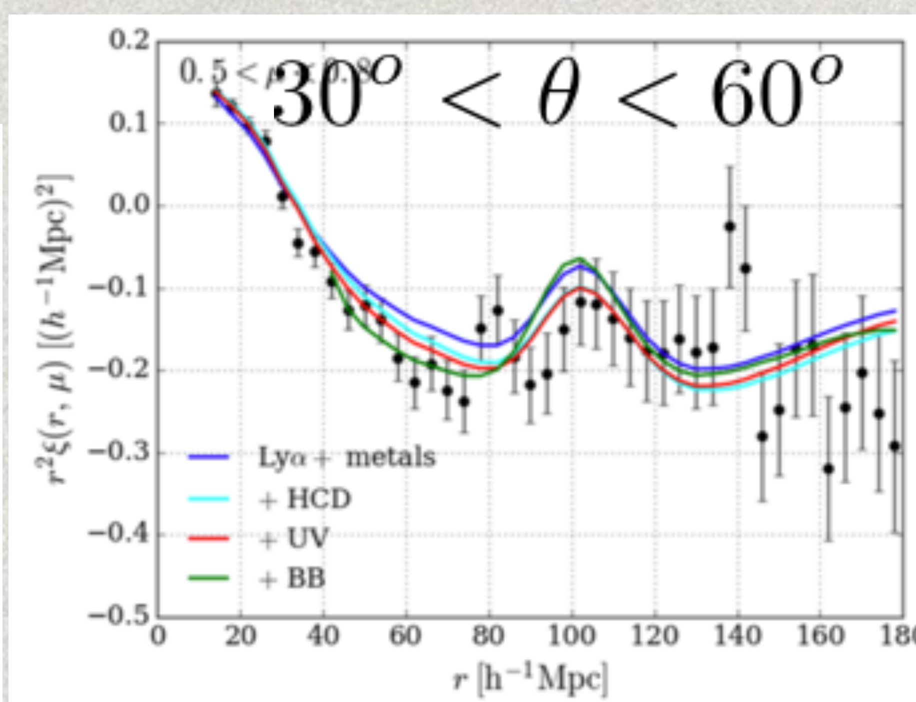
CORRELATION FUNCTION

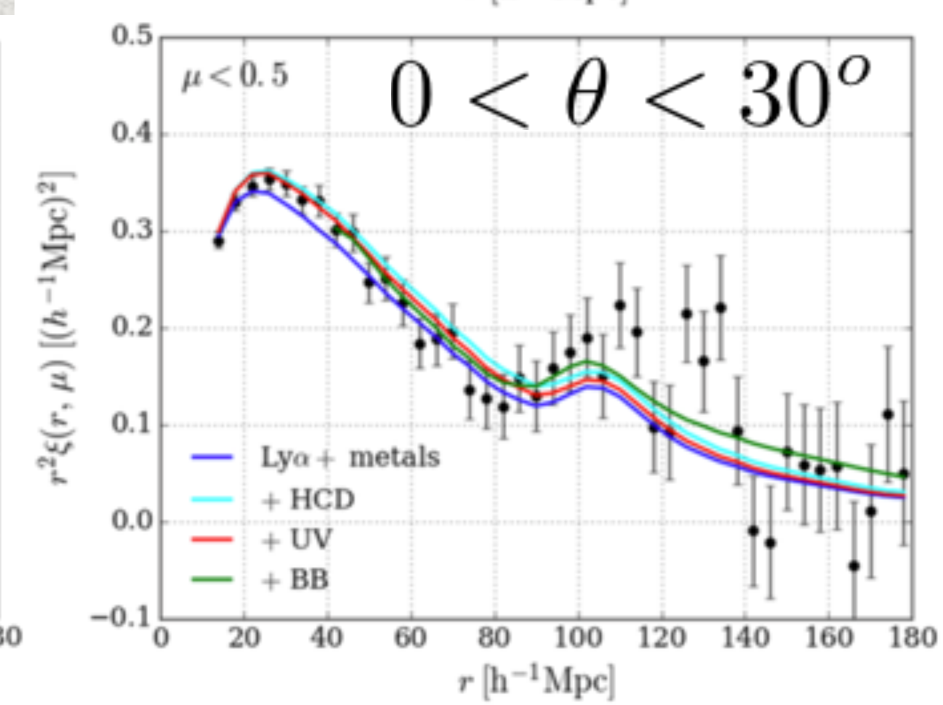


$60^o < \theta < 71.5^o$

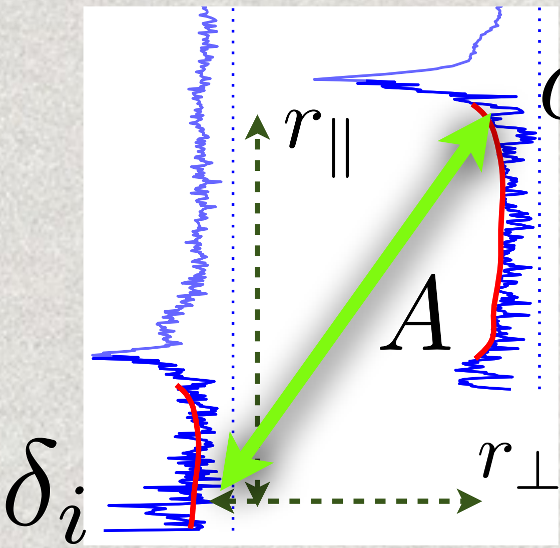


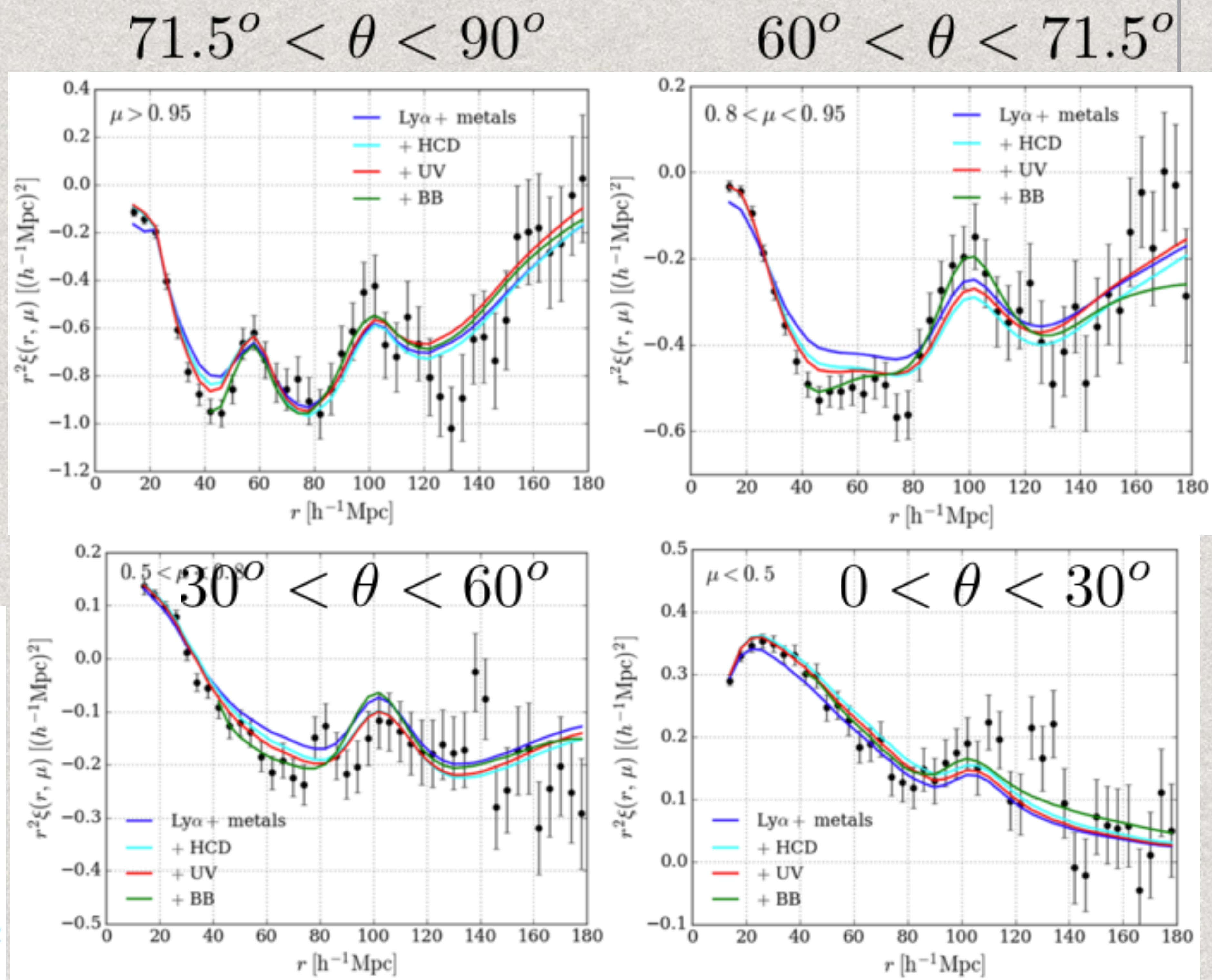


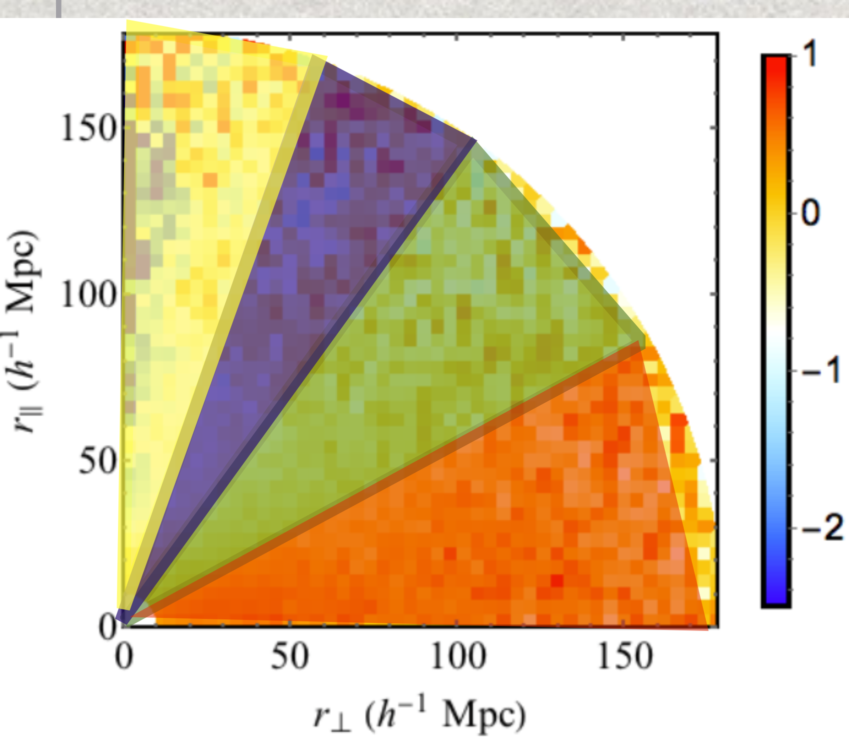




CORRELATION FUNCTION





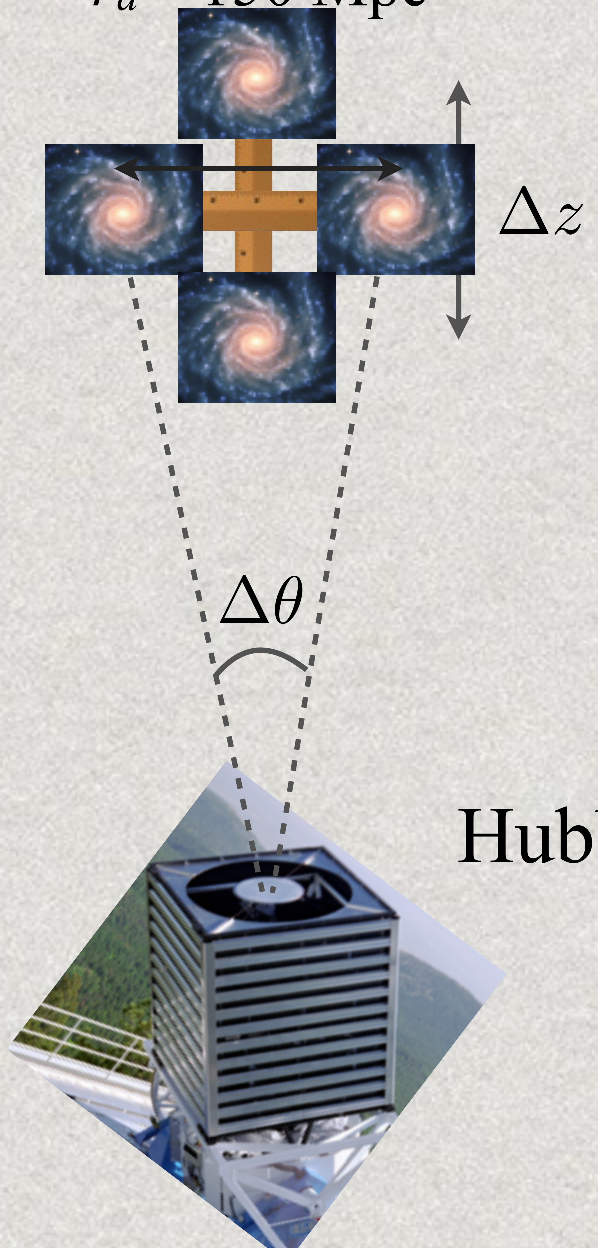


MEASURING BAO SCALE

Baofit (Kirkby++2013, Blomqvist++2015) and github:igmhub/pylya

BAO scale

$r_d \sim 150$ Mpc



Distances

$$\Delta\theta \propto \frac{r_d}{D_A(z)}$$

Hubble's law (in the past)

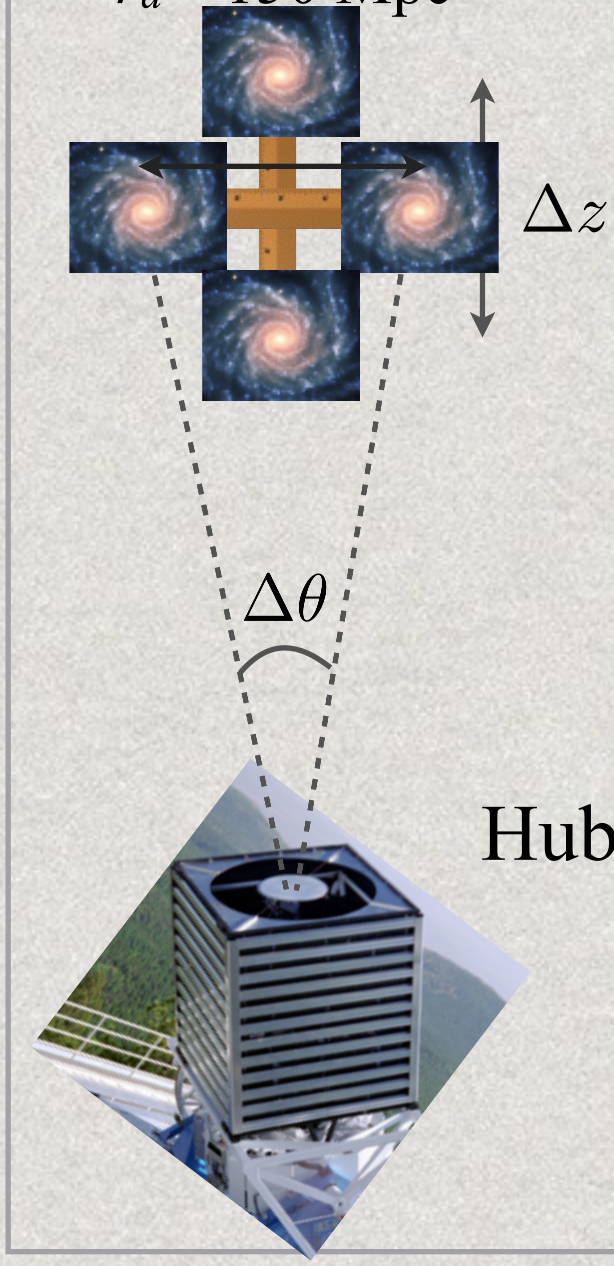
$$\Delta z \propto \frac{r_d}{D_H(z)}$$

MEASURING BAO SCALE

Baofit (Kirkby++2013, Blomqvist++2015) and github:igmhub/pylya

BAO scale

$r_d \sim 150$ Mpc



$$\xi_{\rm model}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) = \xi_{\rm cosmo}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) + \xi_{\rm broadband}(\vec{r})$$

Distances

$$\Delta\theta \propto \frac{r_d}{D_A(z)}$$

Hubble's law (in the past)

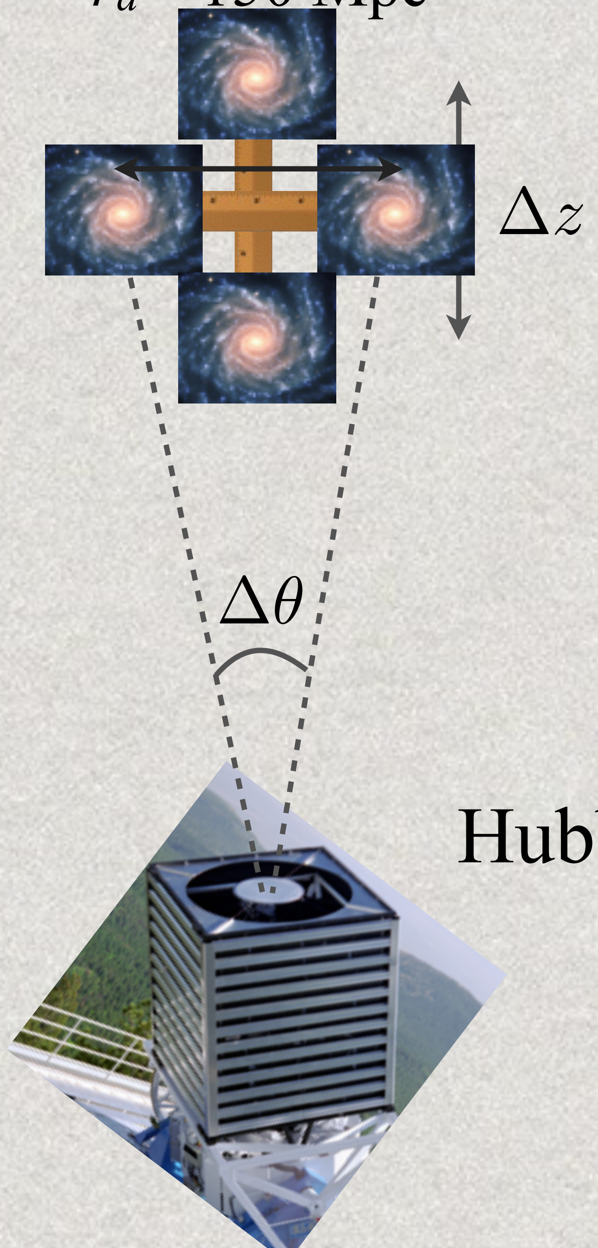
$$\Delta z \propto \frac{r_d}{D_H(z)}$$

MEASURING BAO SCALE

Baofit (Kirkby++2013, Blomqvist++2015) and github:igmhub/pylya

BAO scale

$r_d \sim 150$ Mpc



$$\xi_{\rm model}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) = \xi_{\rm cosmo}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) + \xi_{\rm broadband}(\vec{r})$$

$$\alpha_{\parallel} = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\rm fid}} \quad \text{and} \quad \alpha_{\perp} = \frac{D_A(\bar{z})/r_d}{[D_A(\bar{z})/r_d]_{\rm fid}}$$

Radial BAO

Transverse BAO

Distances

$$\Delta\theta \propto \frac{r_d}{D_A(z)}$$

Hubble's law (in the past)

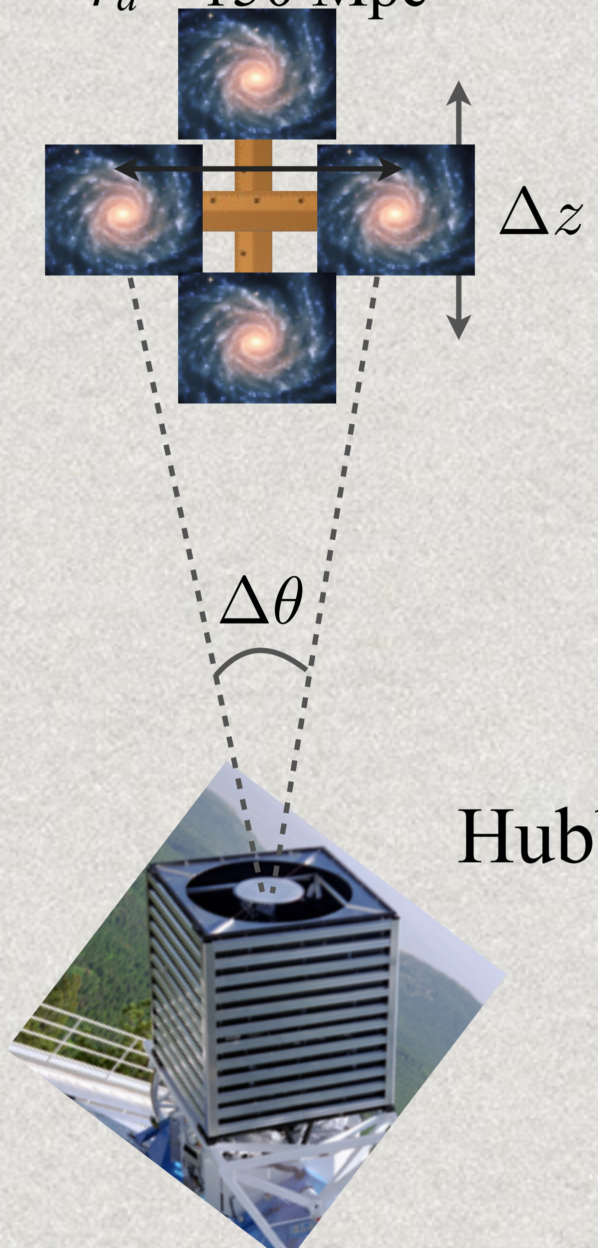
$$\Delta z \propto \frac{r_d}{D_H(z)}$$

MEASURING BAO SCALE

Baofit (Kirkby++2013, Blomqvist++2015) and github:igmhub/pylya

BAO scale

$r_d \sim 150$ Mpc



$$\xi_{\rm model}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) = \xi_{\rm cosmo}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) + \xi_{\rm broadband}(\vec{r})$$

$$\alpha_{\parallel} = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\rm fid}} \quad \text{and} \quad \alpha_{\perp} = \frac{D_A(\bar{z})/r_d}{[D_A(\bar{z})/r_d]_{\rm fid}}$$

Radial BAO

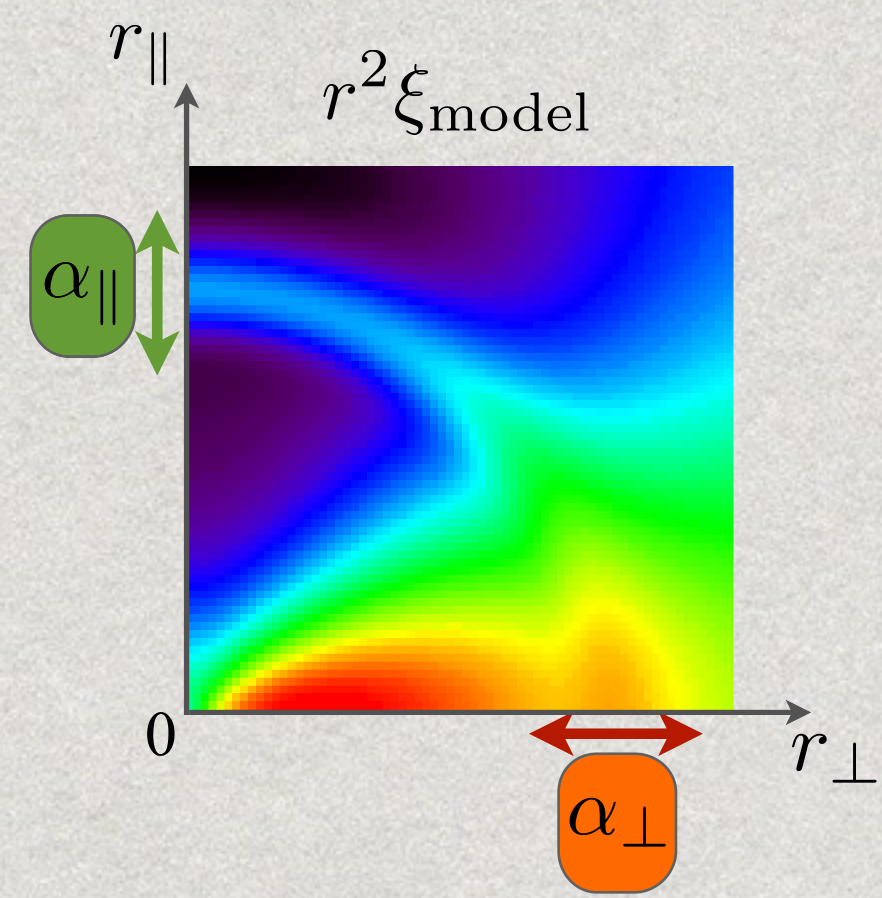
Transverse BAO

Distances

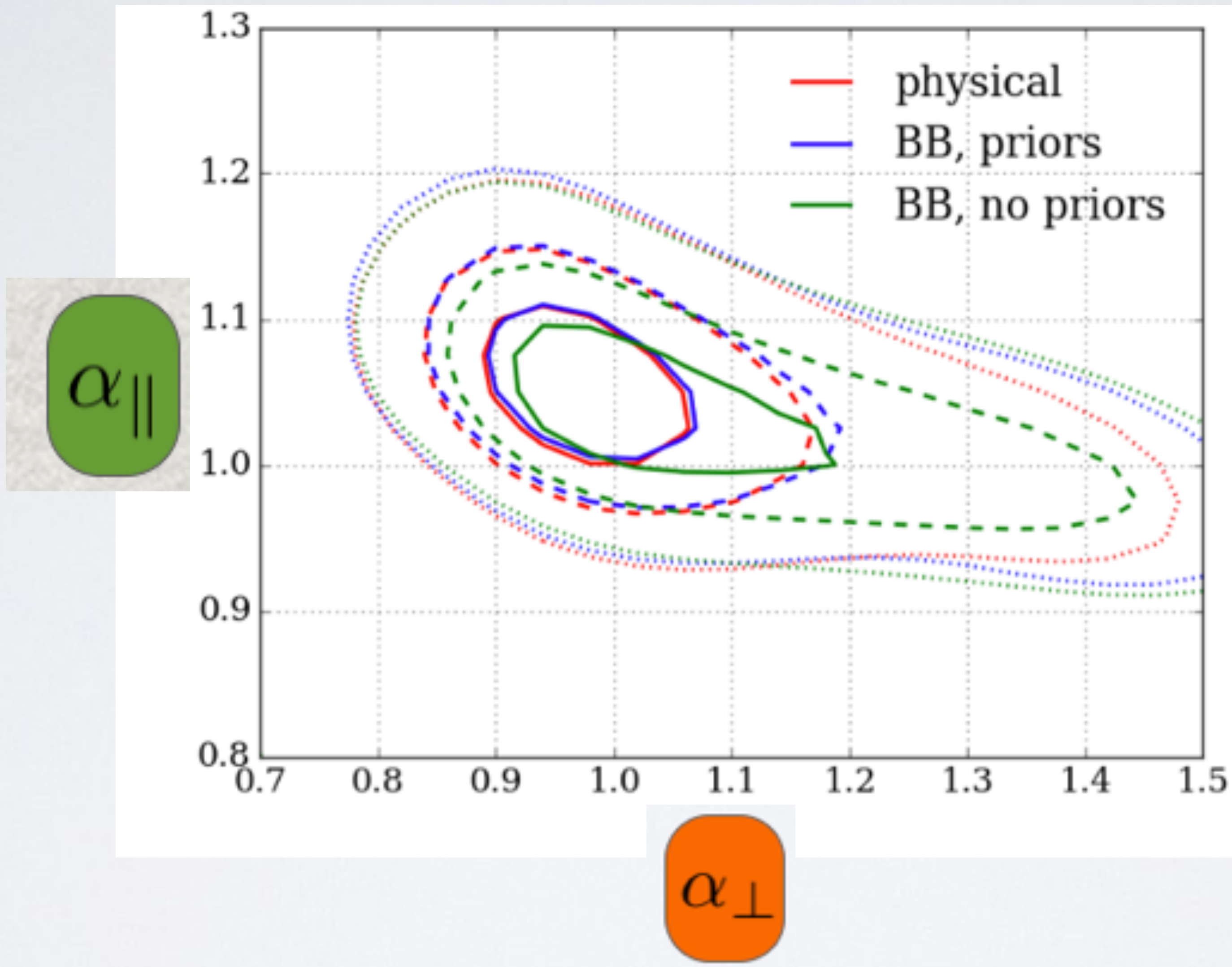
$$\Delta\theta \propto \frac{r_d}{D_A(z)}$$

Hubble's law (in the past)

$$\Delta z \propto \frac{r_d}{D_H(z)}$$



BAO CONSTRAINTS



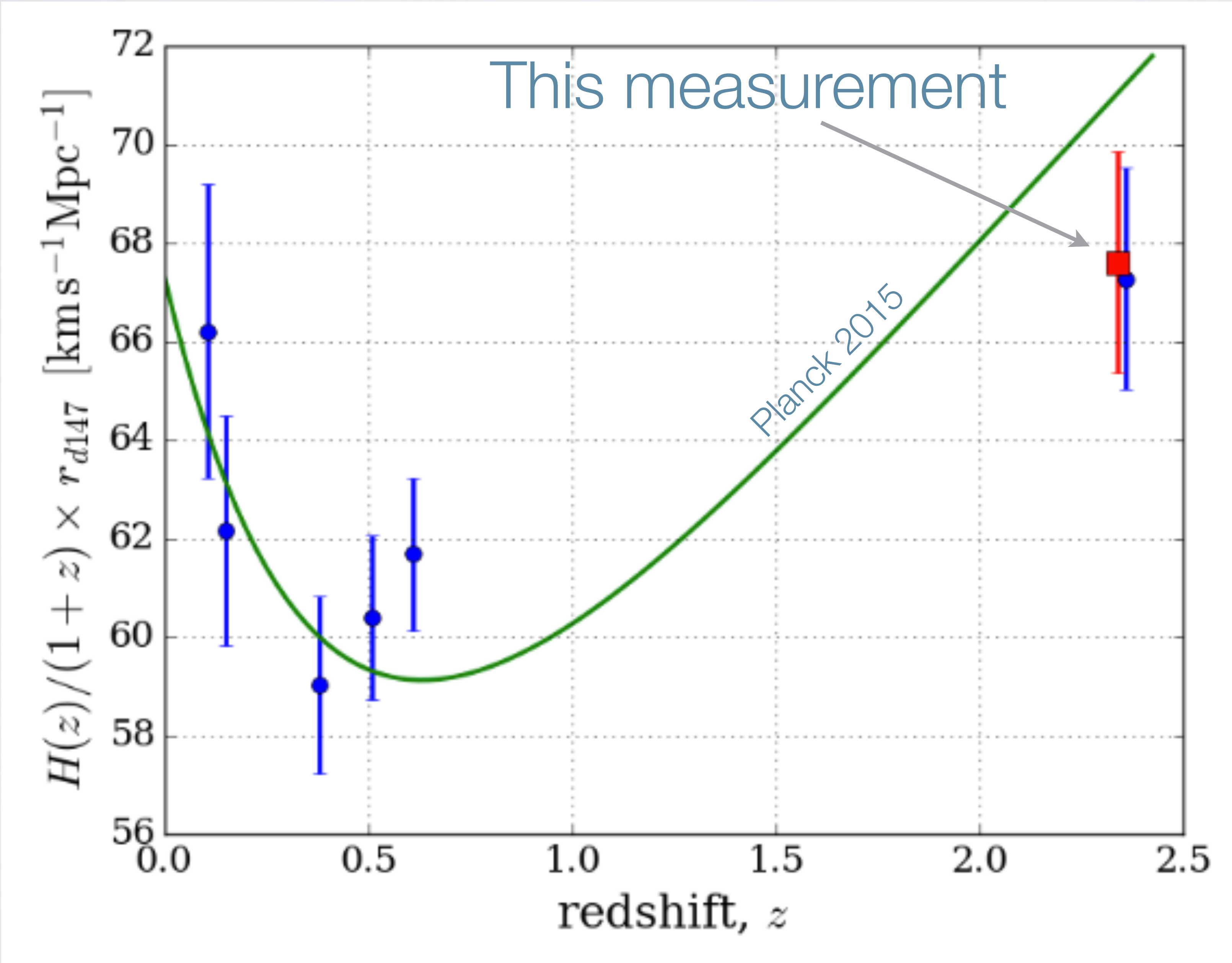
$$\alpha_{||} = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\rm fid}} \quad \text{and} \quad \alpha_{\perp} = \frac{D_A(\bar{z})/r_d}{[D_A(\bar{z})/r_d]_{\rm fid}}$$

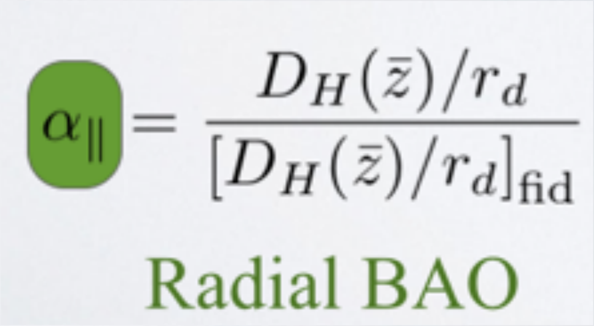
Radial BAO

Transverse BAO

BAO CONSTRAINTS

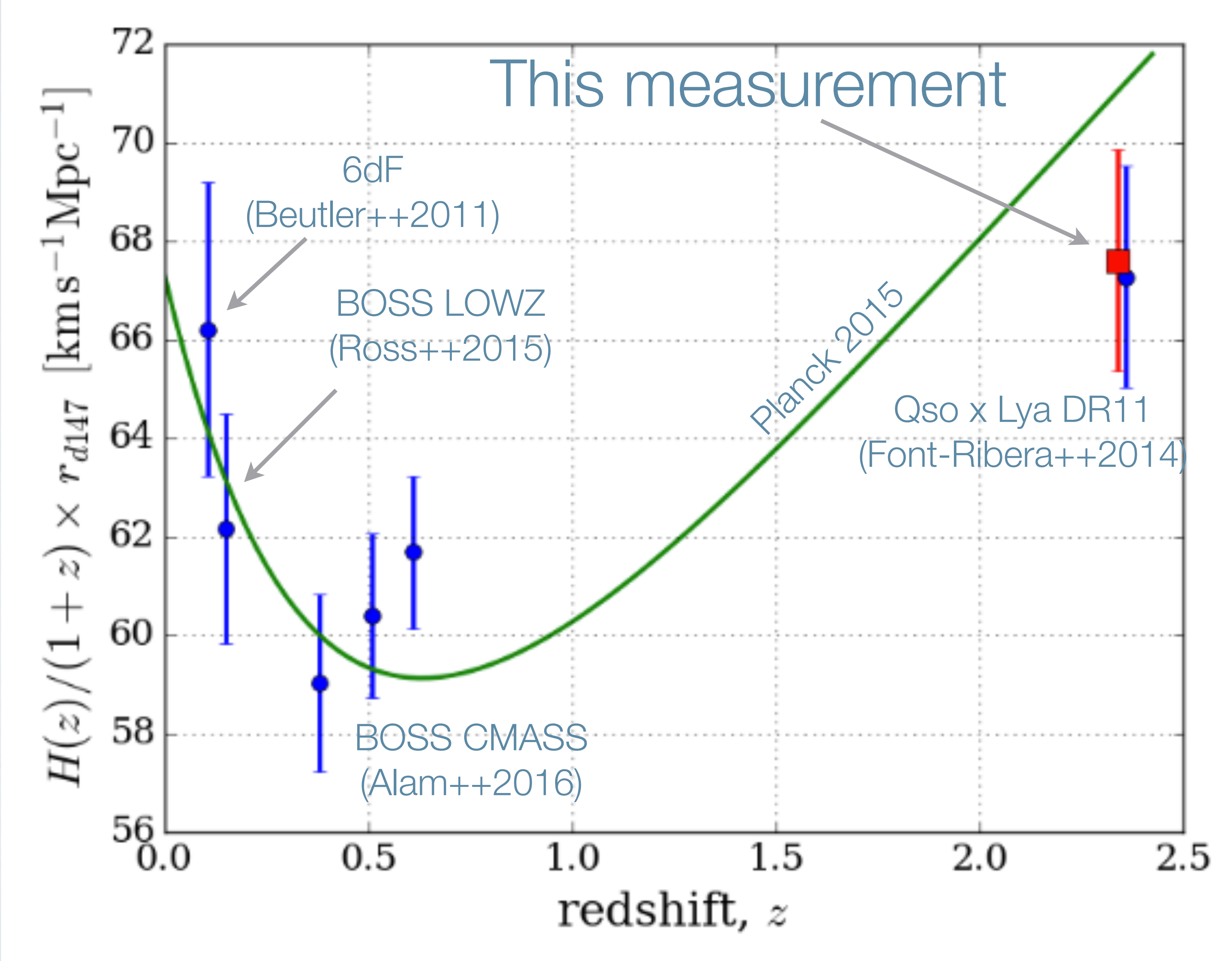
Expansion rate with BAO

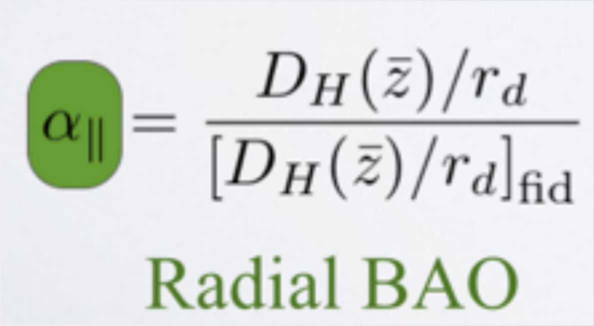




BAO CONSTRAINTS

Expansion rate with BAO

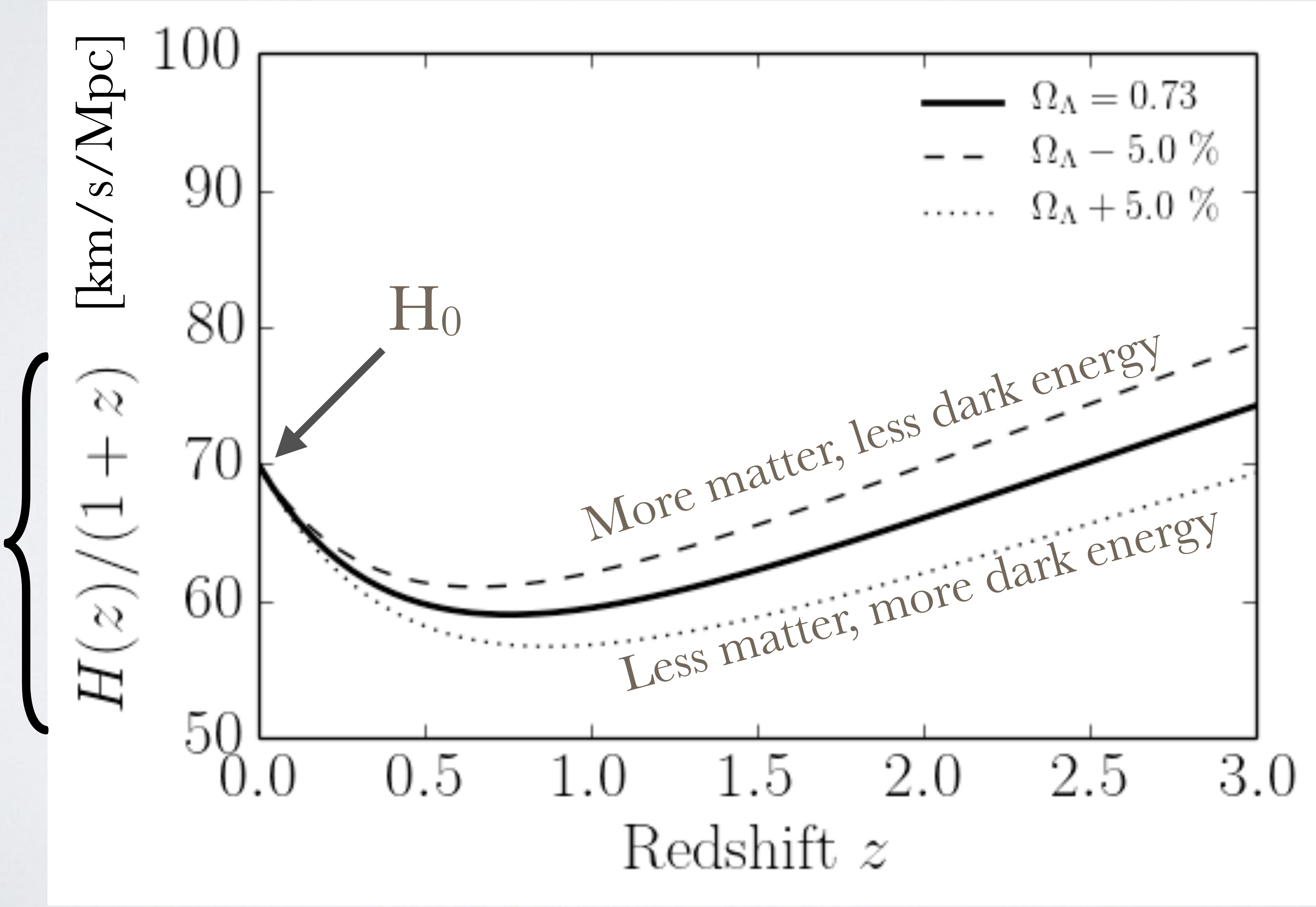




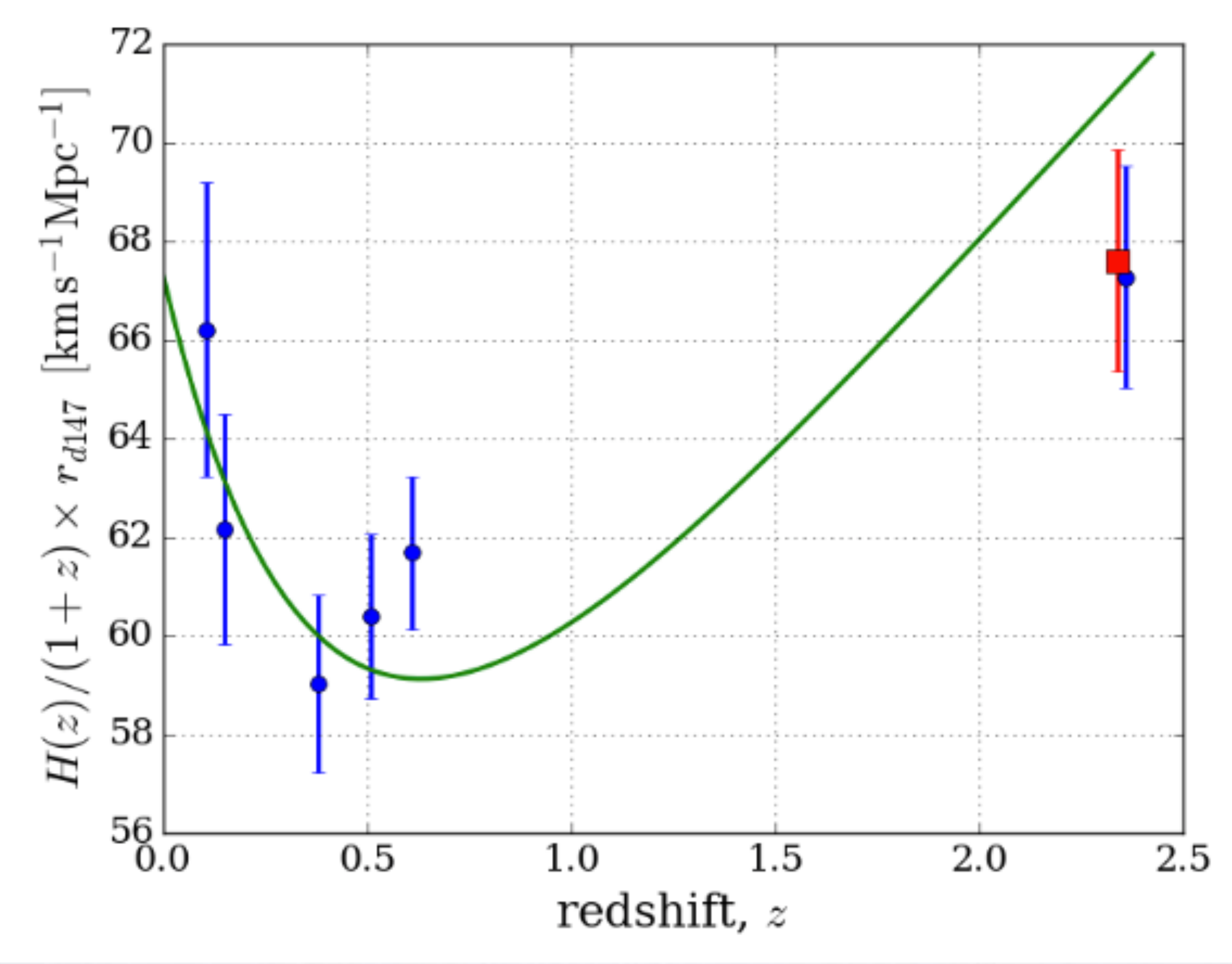
BAO CONSTRAINTS

Expansion rate with BAO

$$\dot{a}(t) = $$



BAO CONSTRAINTS



BAO CONSTRAINTS

$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2 + \Omega_r(1+z)^4\right]$$

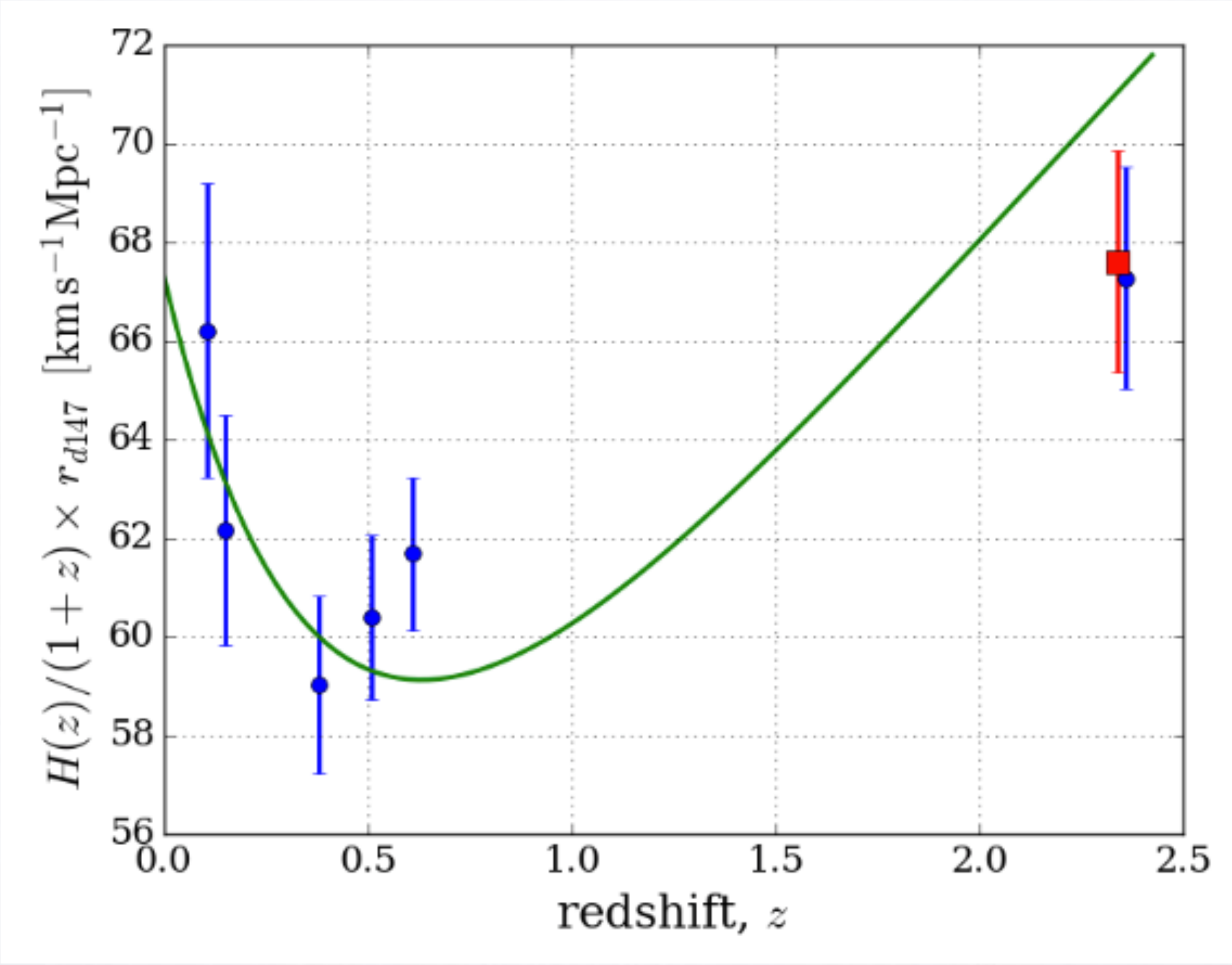
Today

Dark + baryonic matter density

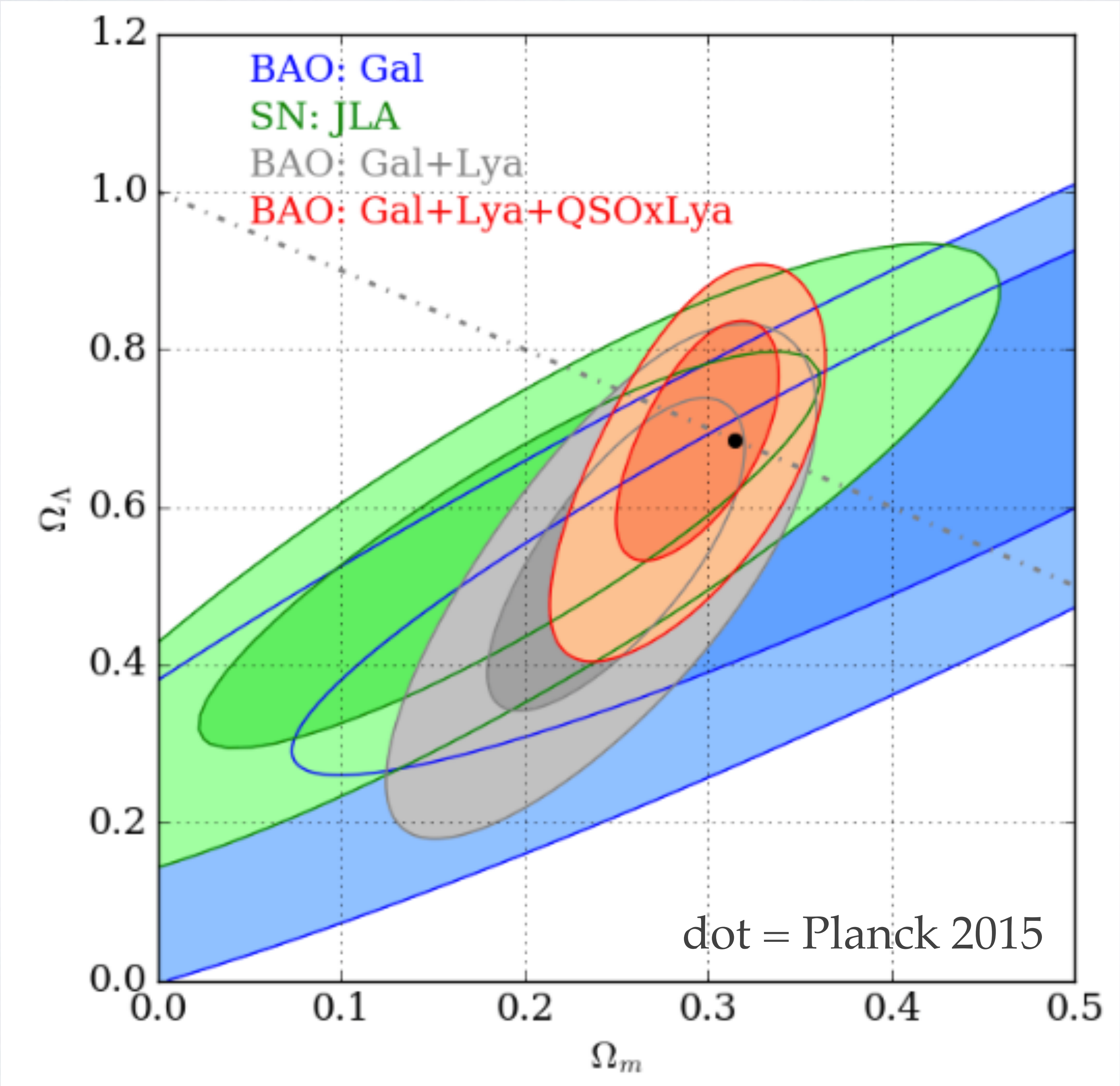
Dark energy

Curvature

Radiation



COSMOLOGY

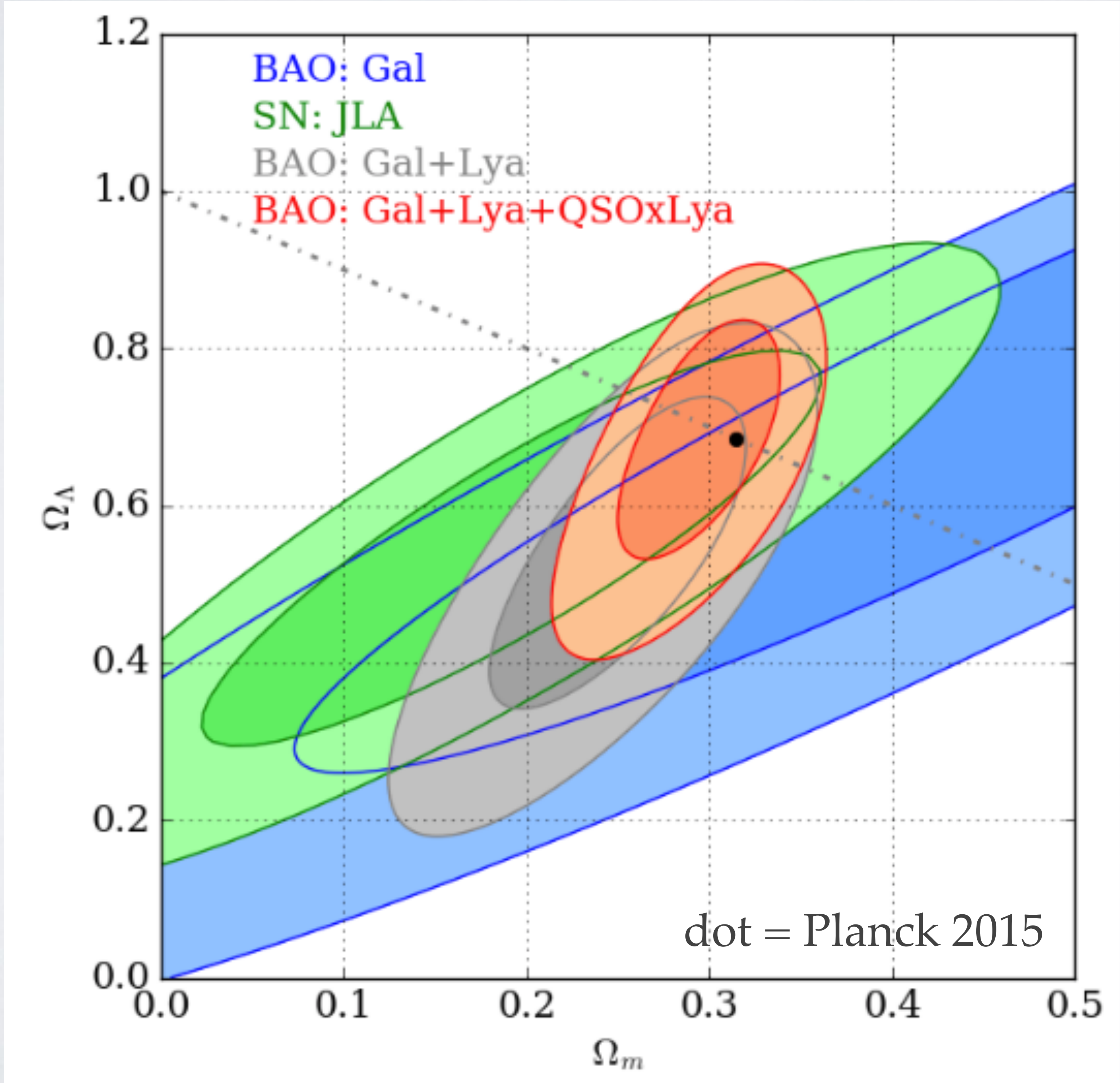


BAO: Gal
SN: JLA
BAO: Gal+Lya
BAO: Gal+Lya+QSOxLya
dot = Planck 2015
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
Ω_Λ
Ω_m

COSMOLOGY

$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2 + \Omega_r(1+z)^4\right]$$

Radiation



DO WE TRUST OUR MEASUREMENT?

LIST OF TESTS

Astrophysical systematics

- contamination by metals: Si, C
- contamination by DLAs, or BALs
- contamination by galactic absorption
- effect of UV background fluctuations
- effect of continuum fitting

Instrumental systematics

- impact of flux calibration
- impact of sky residuals
- impact of fiber cross-talk
- impact of extraction

All tests were performed on data and mock catalogs

Create realistic quasar spectra

JB et al. 2015

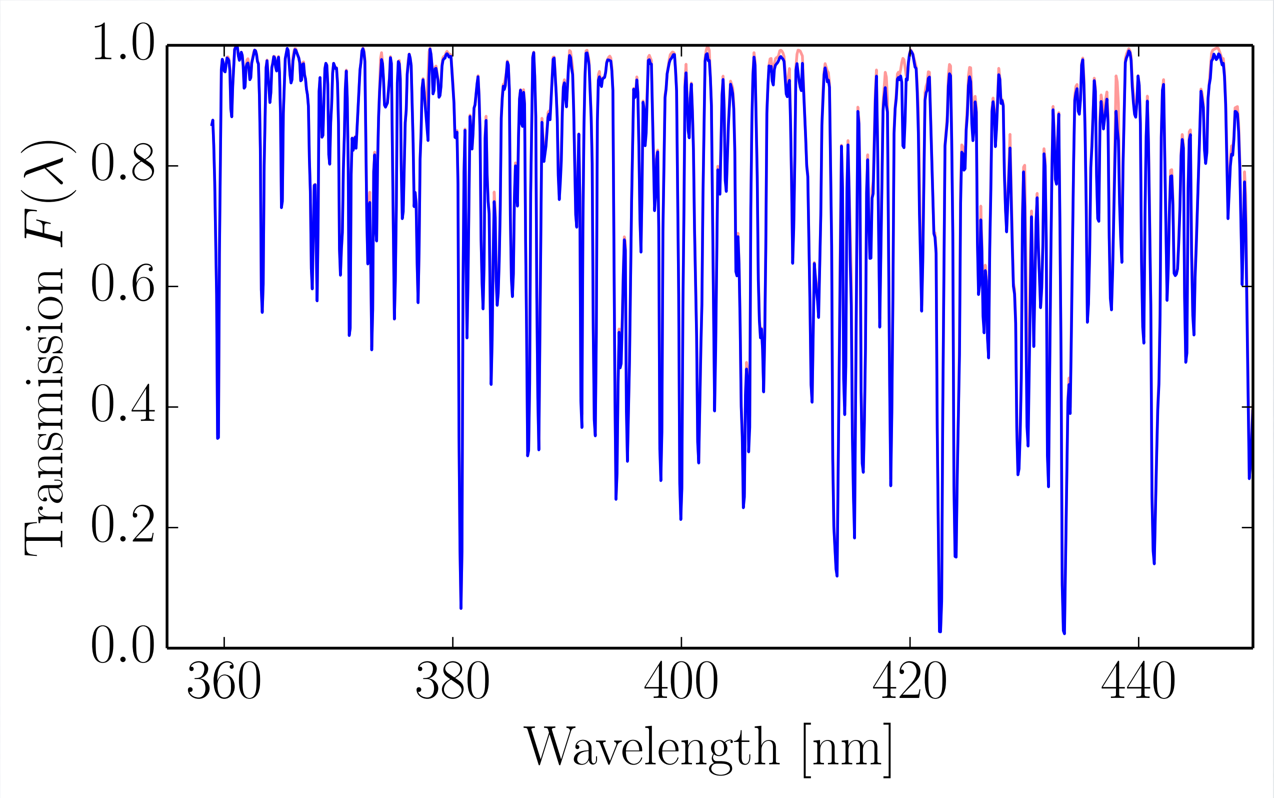
MockExpander package

Create realistic quasar spectra

JB et al. 2015

MockExpander package

- Resolution, binning

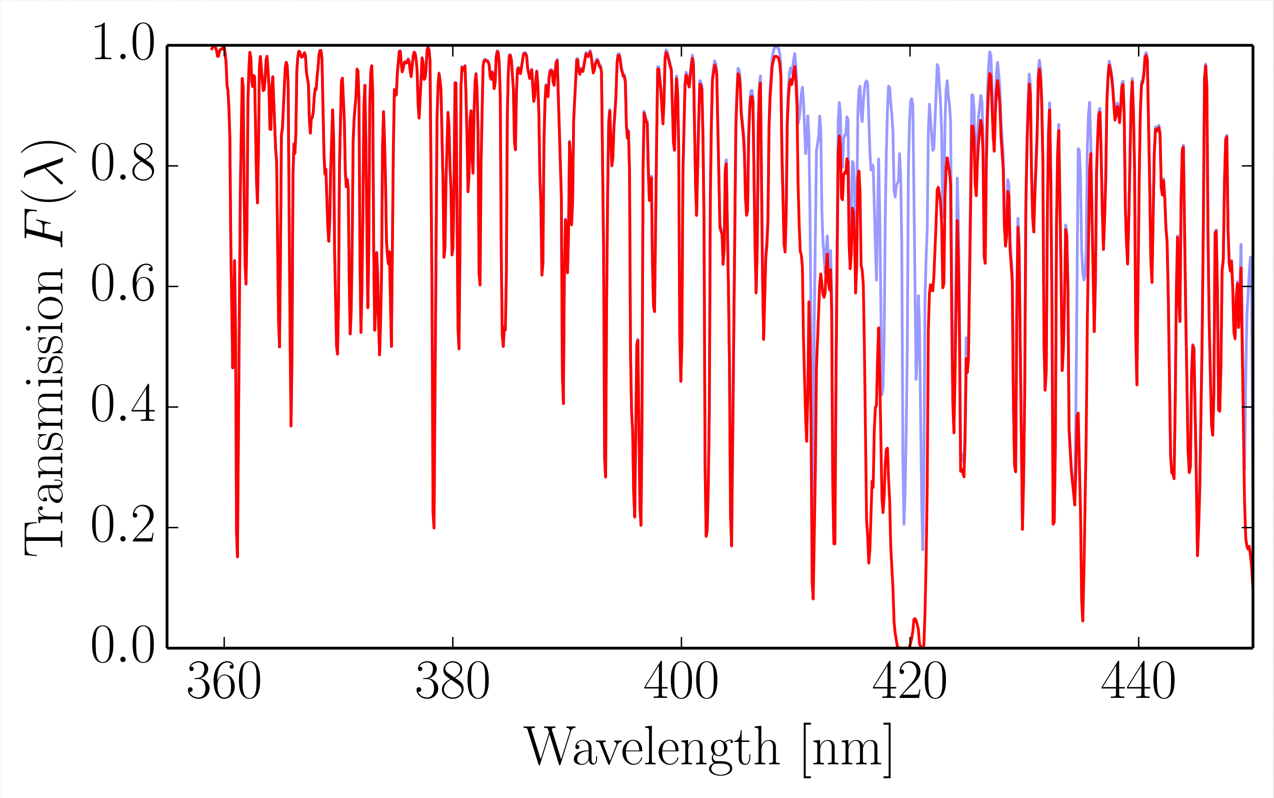


Create realistic quasar spectra

JB et al. 2015

MockExpander package

- Resolution, binning
- High column density systems

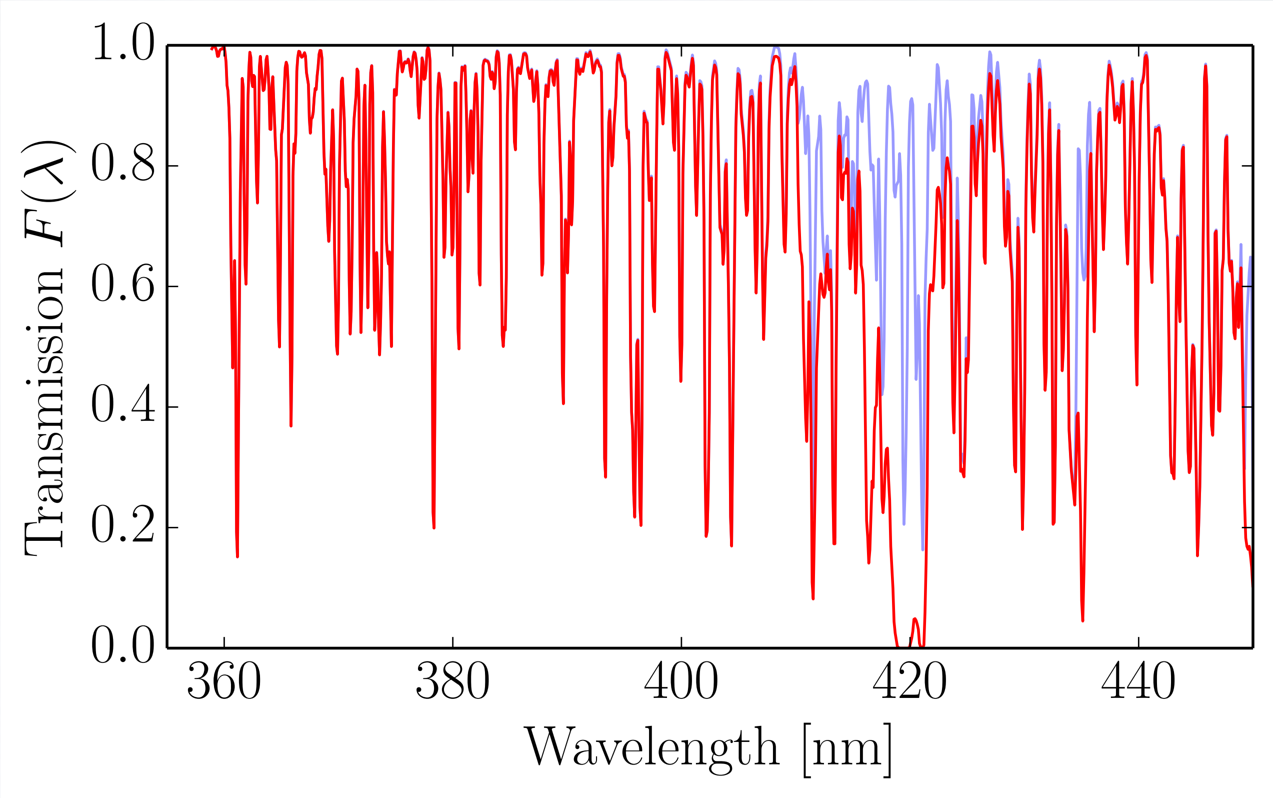


Create realistic quasar spectra

JB et al. 2015

MockExpander package

- Resolution, binning
- High column density systems
- Metals

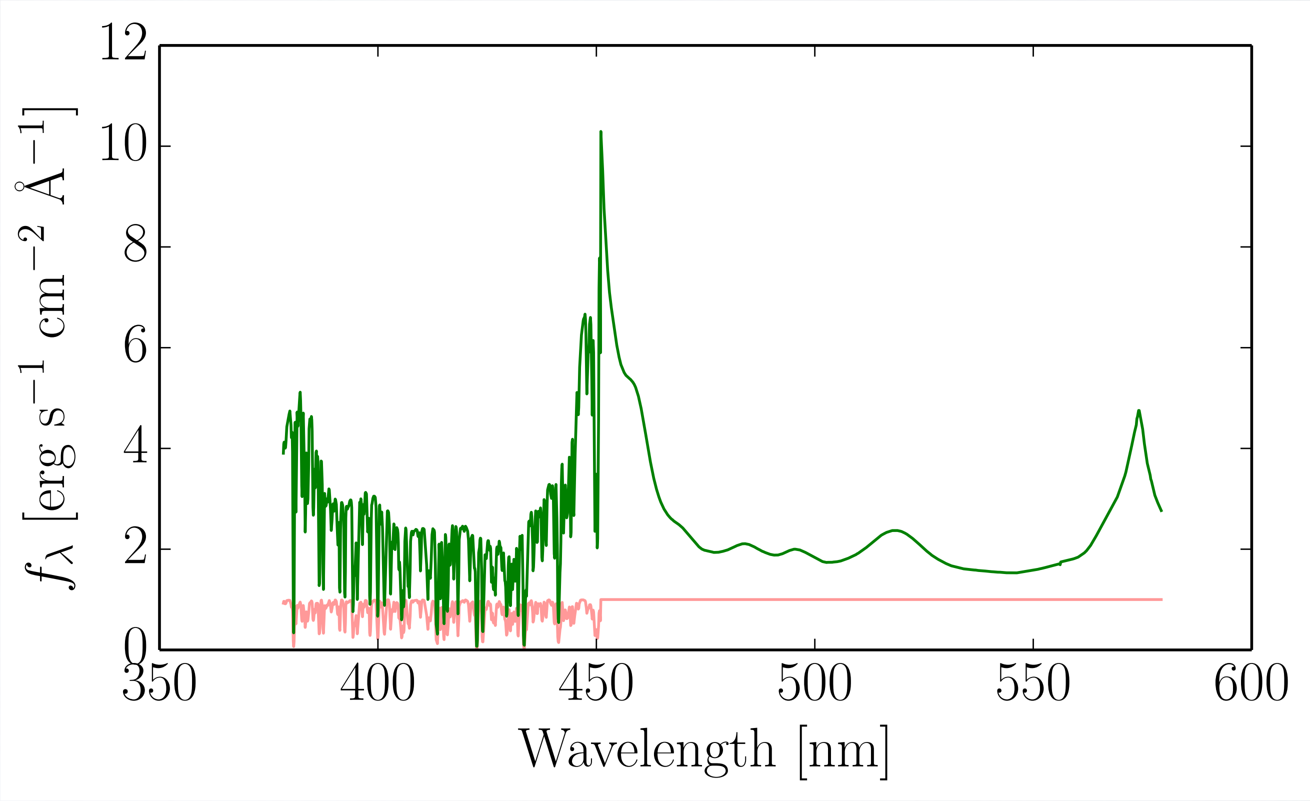


Create realistic quasar spectra

JB et al. 2015

MockExpander package

- Resolution, binning
- High column density systems
- Metals
- Continuum

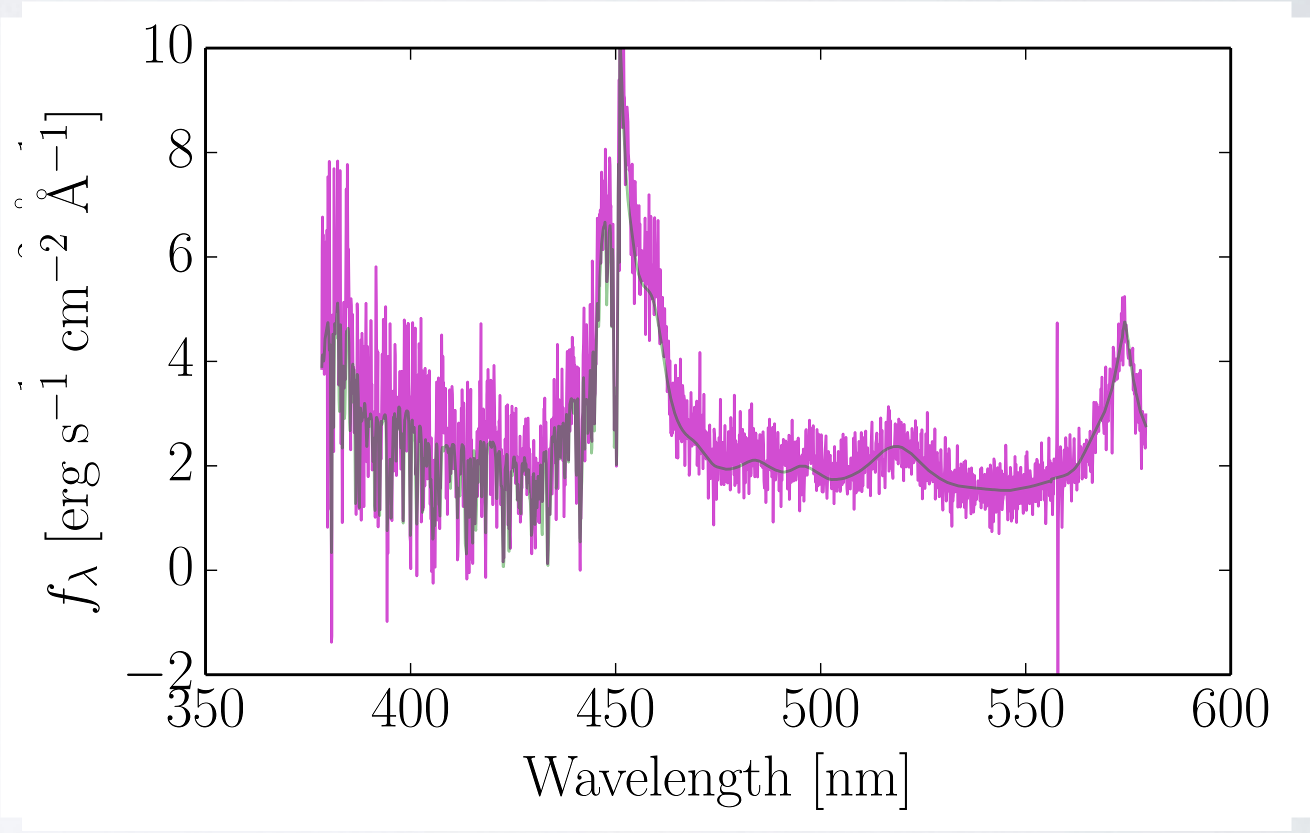


Create realistic quasar spectra

JB et al. 2015

MockExpander package

- Resolution, binning
- High column density systems
- Metals
- Continuum
- Noise

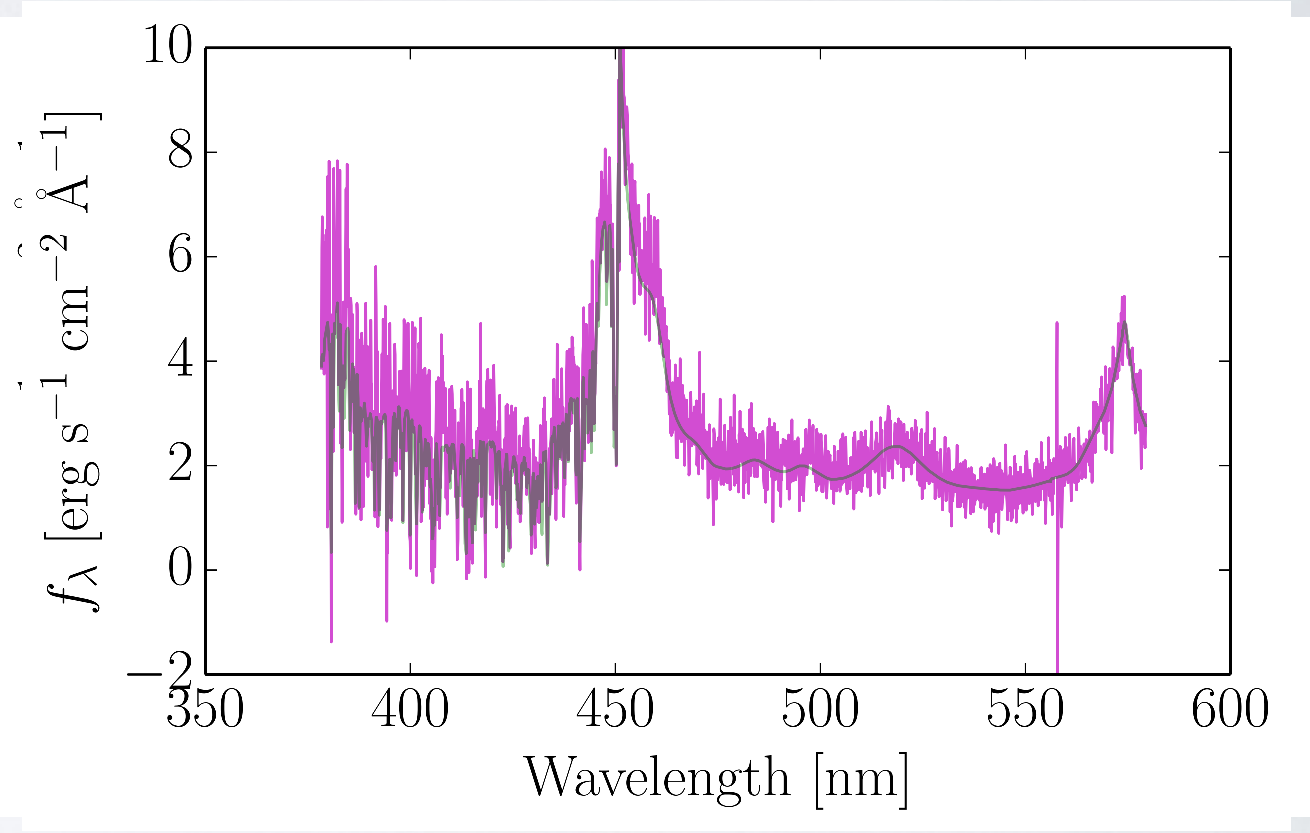


Create realistic quasar spectra

JB et al. 2015

MockExpander package

- Resolution, binning
- High column density systems
- Metals
- Continuum
- Noise
- Sky subtraction residuals

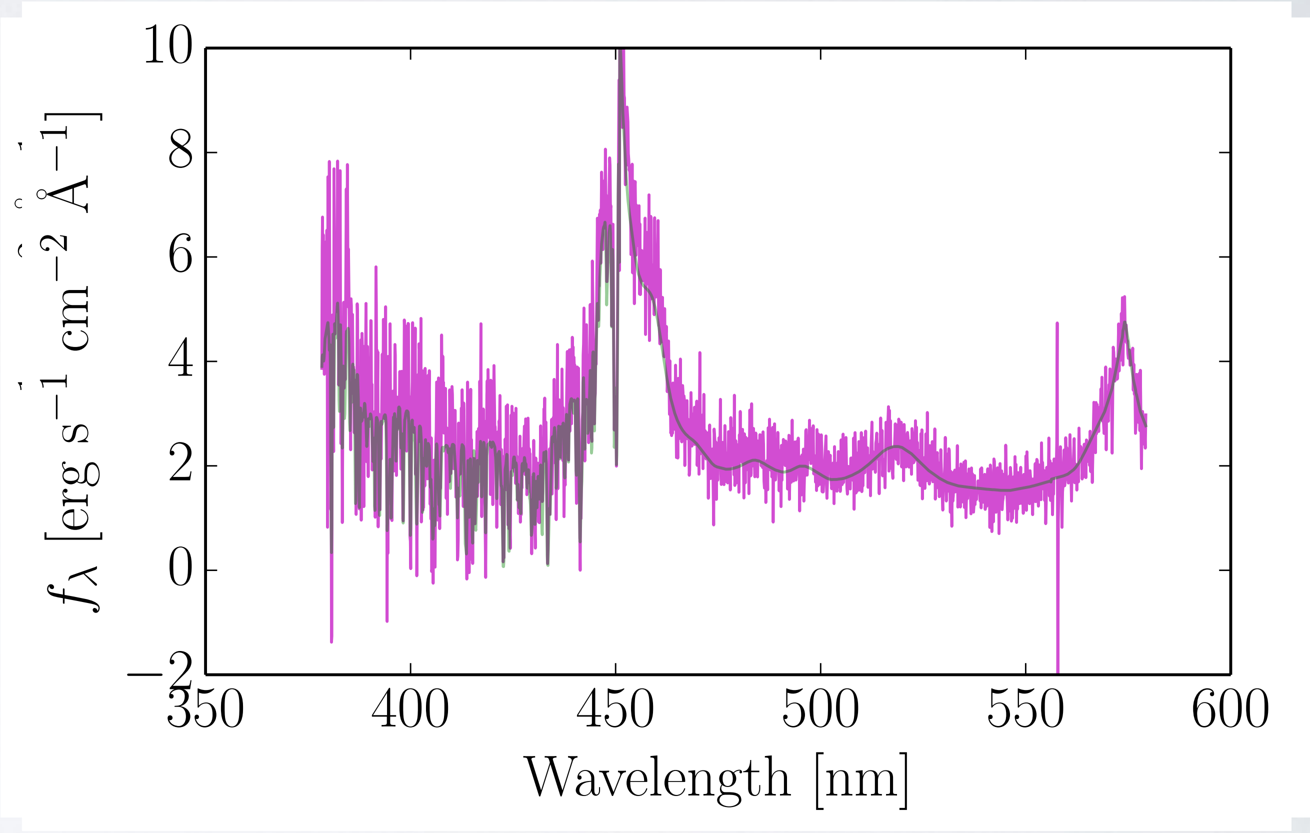


Create realistic quasar spectra

JB et al. 2015

MockExpander package

- Resolution, binning
- High column density systems
- Metals
- Continuum
- Noise
- Sky subtraction residuals
- Observational errors



LIST OF TESTS

Astrophysical systematics

mock set	$\overline{\alpha_\parallel}$ $(\overline{\sigma_{\alpha_\parallel}})$	$\overline{\alpha_\perp}$ $(\overline{\sigma_{\alpha_\perp}})$
Lyα only	0.998 (0.014)	1.002 (0.020)
+continuum	1.000 (0.023)	0.993 (0.040)
+metals (Met1)	0.998 (0.025)	0.993 (0.040)
(or) +metals (Met2)	1.002 (0.023)	0.992 (0.039)
+HCDs (20)	0.995 (0.032)	0.999 (0.058)
(or) +HCDs (21)	0.995 (0.032)	0.995 (0.056)

α's consistent with mock input = 1.0

Instrumental systematics

	$\beta_{\mathrm{Ly}\alpha}$	$b(1+\beta)$	$\alpha_\parallel$	$\alpha_\perp$
Sky model noise	−0.026	−0.002	< 0.001	< 0.001
Calibration noise	+0.047	+0.002	< 0.001	+0.001
Fiber cross-talk	+0.003	< 0.001	< 0.001	< 0.001
ISM absorption	+0.003	< 0.001	< 0.001	< 0.001
Sum	+0.027	< 0.001	+0.001	< 0.001
Quadratic sum	+0.054	+0.002	< 0.001	+0.001

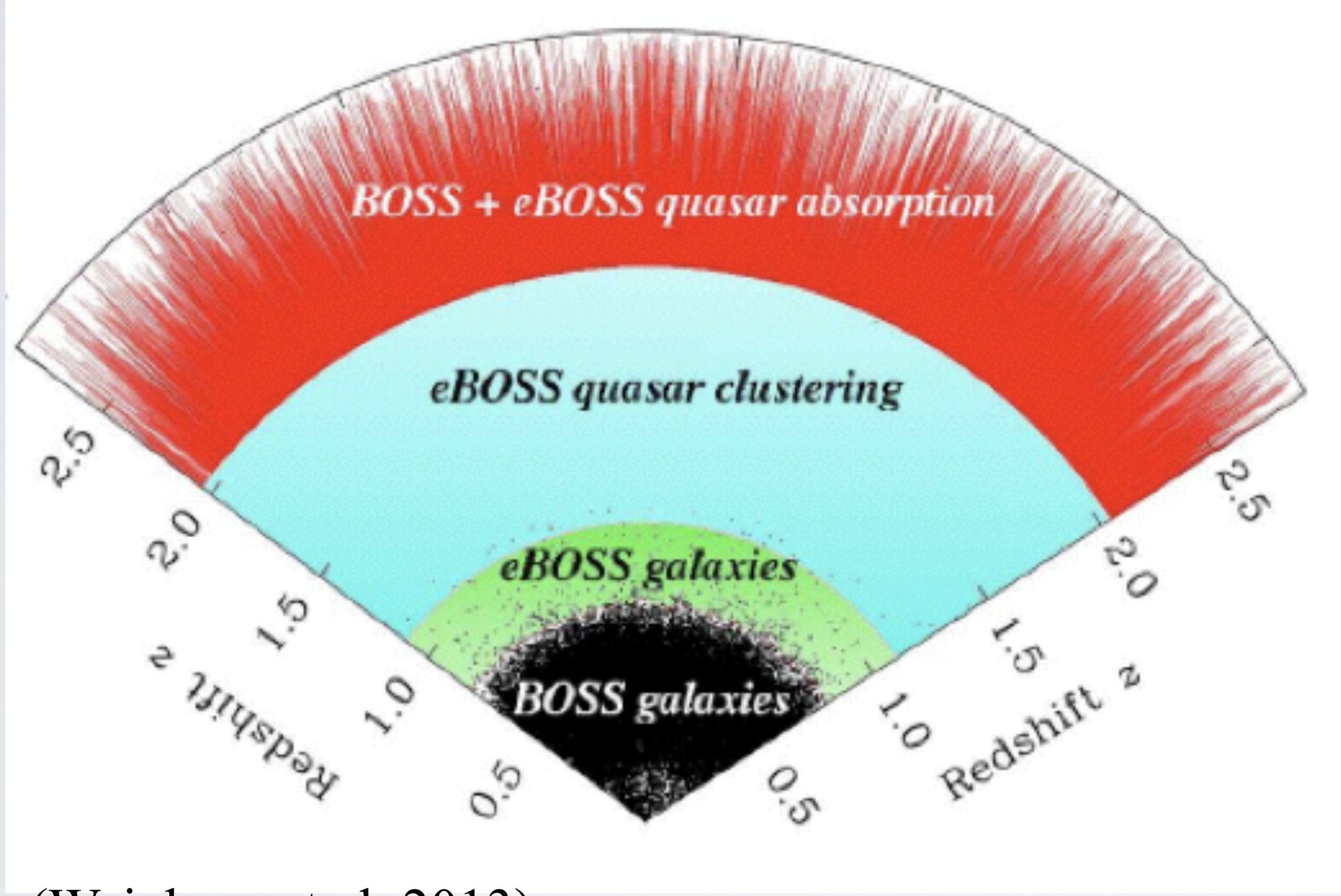
No significant contribution to errors

Surprisingly very robust measurement!

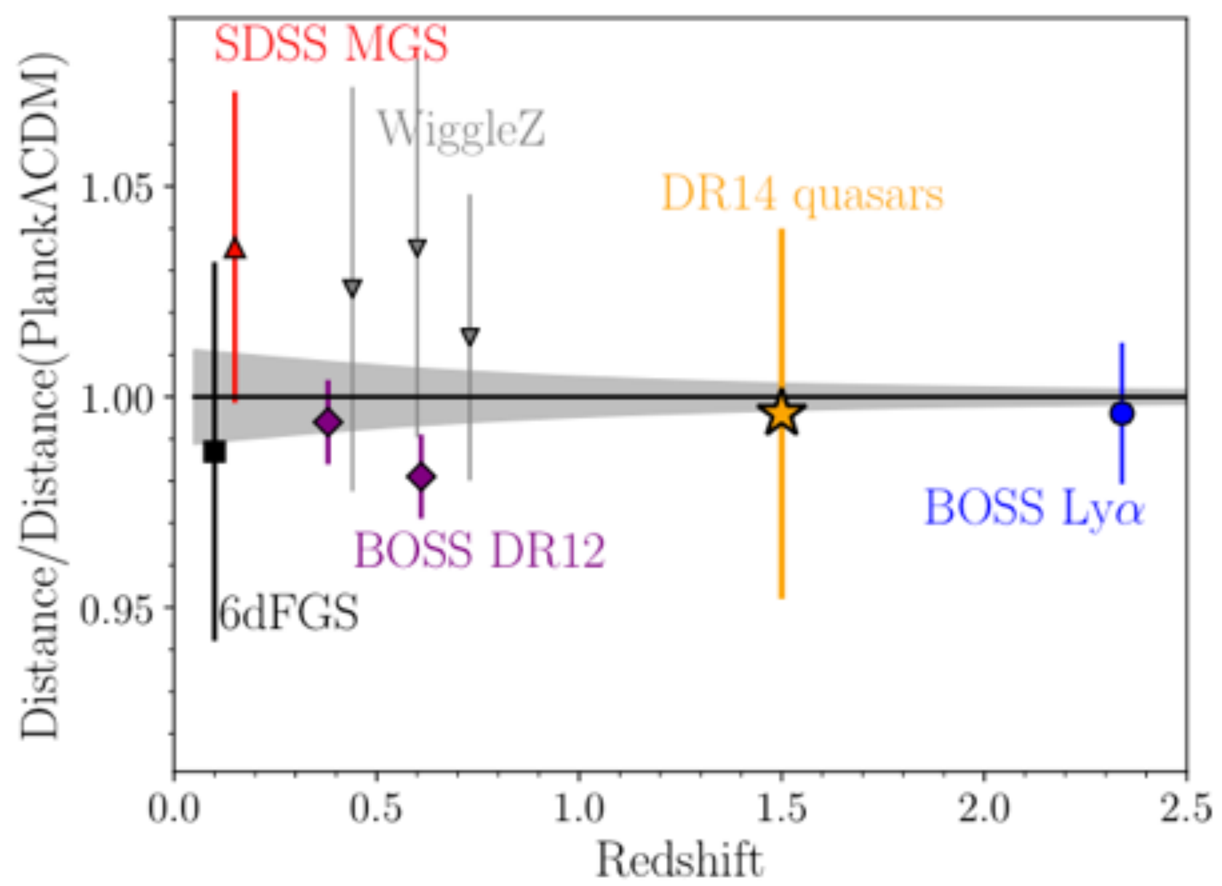
FUTURE

FUTURE

eBOSS



(Weinberg et al. 2013)



First BAO measurement with quasars at z = 1.5 (Ata et al. 2017)

FUTURE

eBOSS

The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX)

The Subaru Hyper-Suprime Camera and Prime Focus Spectrograph (PFS)

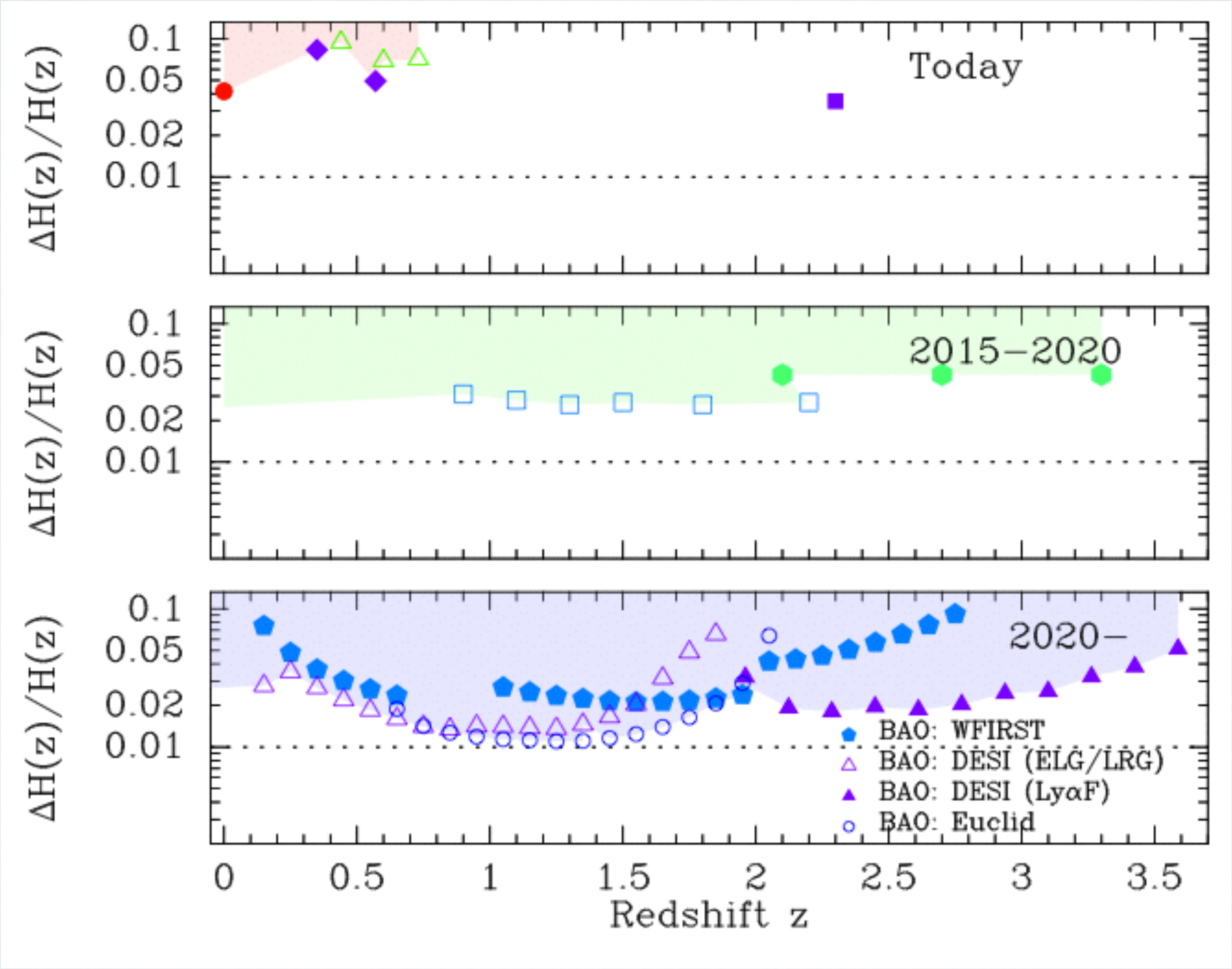
The Dark Energy Spectroscopic Instrument (DESI)

Large Synoptic Survey Telescope (LSST)

Euclid

The Wide Field Infrared Survey Telescope (WFIRST)

FUTURE



(Kim et al. 2013)

Conclusions

- Dark energy is a mystery and we need more data!
- BAO is a robust method to study expansion
- Lyman-alpha forests allow high redshift exploration
- With BOSS, we measure H(z=2.3) to 3%, giving independent detection of Ω_Λ!
- Future surveys are coming soon!